Environmental Studies No. 16

Sump Studies III — Biological Changes in Permafrost Terrain Adjacent to High Arctic Oil and Gas Wellsites

Northern Affairs Program

D.W. Smith
T.D.W. James
Department of Botany and Genetics
University of Guelph

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SUMMARY AND RECOMMENDATIONS

Chemical contamination of soils and vegetation by spilled drilling fluids was evident at all six High Arctic wellsites. Sodium, potassium and chloride were the chief inorganic contaminants of soil. Available levels of sodium and potassium were higher than background over extensive areas adjacent to sumps but did not exceed phytotoxic limits. High levels of available chloride showed a similarly wide distribution and locally exceeded phytotoxic limits.

Plants growing in contaminated areas accumulated greater concentrations of sodium, potassium and chloride than those in undisturbed areas. However, salt damage to plants, such as leaf discoloration and shedding, was not obvious.

Heavy metal contamination of soil close to sumps occurred at some sites, but available levels were low. These ions; e.g. zinc, copper and chromium, did not reach phytotoxic concentrations and did not appear to have any significant effects on the vegetation.

Toxic contamination by drilling fluids was probably in part responsible for eradication of plants close to sumps and reductions in species number and abundance further downslope. However, this could not be conclusively established for two reasons: 1) chemical toxicity could not be distinguished from the effects of physical disturbance with which it was commonly associated; and, 2) data describing undisturbed soil and vegetation prior to drilling were unavailable.

Contamination of the terrain was not a consequence of sump failure. Widespread distribution of drilling chemicals chiefly resulted from leaching and erosion processes associated with placement of sumps on high parts in the terrain, either on slopes or immediately adjacent to slopes. Overfilling of sumps, mixing of sump wastes with sump infill materials and inadvertant spillage of mud additives in the vicinity of the drilling rig were other causes of contamination.

Our following recommendations are based on the premise that sumps are an effective means of drilling waste containment in the High Arctic but that the bulk of the problems resulting in terrain contamination can be either eliminated or at least minimized. These recommendations are not ranked in order of relative importance.

1) Sumps should continue to be used for drilling waste disposal in the High Arctic.

Drilling fluids quickly freeze *in situ* in the High Arctic and sumps are effective as a means of waste containment. Chemical contamination of terrain at the sites studied was not a consequence of sump failure but was chiefly a result of poor sump location, problems during drilling, and sump rehabilitation.

2) Sumps should not be located on slopes or topographic high points immediately adjacent to slopes. Drilling sumps should be located in shallow, natural depressions.

Sumps were perched on high topographic positions at all the wellsites studied and at some sites; e.g. Cape Fleetwood L-21, they were located on slopes. As a consequence, drilling wastes or chemically-contaminated sump infill were widely distributed by the downslope movement of snowmelt. In many cases, moving the sump location by 80-100 m would have placed it in flat, plateau terrain less susceptible to downslope run-off and erosion. The best location for a sump is in a small depression close to the drilling rig. This would allow a reduction in sump construction and provide better containment of the drilling wastes and fill with less terrain disturbance.

3) Selection of sump location should only be made after onsite inspection during the snow-free period.

Locating the sump in a natural depression will necessitate making onsite inspection in the snow-free period prior to drilling. Aerial photography provides some information on site conditions, but variables affecting selection of sites for sump construction can only be determined by field appraisal.

4) Waste fluids should be sampled at discharge outlets to the sump and analyzed prior to infilling.

Sample collection in one litre plastic containers should be made weekly throughout drilling and at times of bulk fluid discharge when the mud system is changed and when the well has been completed. Ion analysis should focus on available levels of Na, K, Cl and the commoner heavy metals in mud additives, e.g. Zn, Cu and Cr. Responsibility for sampling and analysis should lie with the oil company. Results should be released to the regulatory agency.

An estimation of sump chemical contents prior to infilling would permit appraisal of possible toxic effects on surrounding biota if spillage occurred during or after sump rehabilitation. Obtaining a representative sample of drilling fluid is difficult due to the great heterogeneity in sump contents. Further sampling problems occur during winter operations when drilling fluids quickly freeze after discharge. Repeated sampling at fluid discharge points to the sump would be required.

5) More care is needed to avoid spilling bags of drilling chemicals. If such spillage occurs, the chemicals and contaiminated surface soil must be immediately transferred to the sump.

Spilled bags of drilling chemicals are a potential source of phytotoxic contaminants. Local toxic effects may be severe if this spillage is not cleaned up and more widespread contamination can occur if the spillage is carried by snowmelt. Spilled bags of drilling chemicals were observed near the sumps at Robert Harbour K-07 and Chads Creek B-64.

6) More care is needed to avoid spillage of fluids at the wellhead. If such spillage occurs, drilling mud deposited on the surface and contaminated soil must be transferred to the sump prior to infilling.

Surface spillage of mud waste at the wellhead can lead to significant contamination of downslope areas, e.g. at Robert Harbour K-07 and Chads Creek B-64.

7) Better planning in initial sump construction and in dealing with drilling problems leading to deeper wells should be required by IAND. Government officials must be consulted on measures to deal with fluid quantities larger than expected before sumps overflow.

Surface spillage of drilling fluids due to sumps overflowing leads to extensive chemical contamination of surrounding terrain, e.g. at Chads Creek B-64. Damage to the environment may be severe, especially if dikes are built to contain the spilled fluids or additional sumps are constructed. Non-containment of drilling fluids occurs due to construction of too small a sump for a given operation, or if a well is drilled deeper than originally planned.

8) Extension of sumps in use or construction of additional sumps during operations must be avoided, and must under no circumstances be allowed at times when the ground surface is unfrozen.

Transfer of excess drilling fluids to nearby sumps in use should be considered. Construction of additional sumps, only, should be made in consultation with IAND officials.

Extension of the original sump or construction of additional sumps results in considerable terrain disturbance (especially when the ground surface is unfrozen), mixing of sump fluids with overburden, and scattering of drilling fluids on the tundra. Damaging effects of secondary sump construction in the warm season were most apparent at Chads Creek B-64.

9) More care is needed during infilling to avoid mixing of sump contents with overburden. Infilling of sumps must be completed only after the contents have completely frozen.

Upwelling of unfrozen sump fluids during infilling can result in serious spillage and chemical contamination of surrounding terrain.

Mixing of sump wastes with fill materials during infilling can lead to chemical contamination. Melting of contaminated fill in spring, coupled with run-off, can result in widespread dissemination of drilling chemicals. This process appeared to be responsible for high levels of drilling fluid contaminants in the soil downslope of sumps at Cape Fleetwood L-21 and Robert Harbour K-07.

10) Infilled sumps should be mounded to allow for subsequent slumping of fill material.

This is especially important when sumps have to be located in topographic positions subject to sheet and/or gully erosion. Use of fine sand or finer material to infill sumps should be avoided wherever possible. At locations where its use is unavoidable, addition of a top layer of coarse gravel would help prevent sheetwash of overburden downslope.

Snowmelt water draining across infilled sumps can result in the deposition of an overburden of fill materials downslope. Contamination by potentially toxic chemicals contained in the eroded material accompanies its downgrade movement. The combined effects of burial and chemical contamination will result in the death of large areas of vegetation. Overburden burial of vegetation and subsequent mortality was most widespread where fine sand was used to infill sumps, e.g. at Cape Fleetwood L-21 and Robert Harbour K-07. Burial of vegetation by overburden was not a problem at sites such as Bent Horn N-72, Charles Point G-07 and Apollo C-73 where coarse gravel and crushed rock were used as infill.

11) Controlled spillage of drilling fluids should be completed in polar desert, clay-lowland and wet arctic meadow terrain to define response of High Arctic vegetation to drilling chemicals in the soil in the absence of mechanical disturbance.

General procedures at each location should include:

a) collection of soil and vegetation data prior to spillage;

b) replicated spillage of drilling fluids (mud plus supernatant) used in the High Arctic to include wide concentration ranges of the common contaminants Na, K and Cl (use of a "typical" fluid is unfeasible owing to the heterogeneity in drilling fluids);

c) replicated spillage of supernatant from the drilling fluids used in (b) (use of supernatant gives a measure of chemical toxicity without the complicating effects of plant burial by mud, supernatant is also dispersed more widely than drilling mud and studies in the Low Arctic indicate that it is the primary cause of chemically-related vegetation damage at wellsites);

d) replicated drilling fluid spills in summer and winter;

e) detailed chemical analysis of spilled fluids;

f) controlled environment studies in the laboratory to define causal agents of plant mortality;

g) measurement of soil and vegetation in experimental areas over a minimum of five years (initial plant response to chemical contamination may be rapid, but a long recovery period is anticipated owing to the slow growth rates of most High Arctic species; sampling over five years would allow for assessment of recolonization rates, decomposition rates of plant debris rich in ions taken up from contaminated soil, and rates of leaching of toxic materials from the soil).

12) Traffic of tracked vehicles on areas adjacent to sumps must be minimized when the surface ground is frozen and prohibited when it is thawed.

Guidelines for vehicle movement should be worked out by IAND officials and company personnel in the field after onsite inspection. These guidelines should take into account terrain, soil and vegetation characteristics, and drilling requirements at each site. Restrictions on vehicle movement must be rigorously enforced at sites in areas of arctic meadow vegetation; e.g. Bent Horn N-72, and well-vegetated clay soils, e.g. Chads Creek B-64.

Tracked vehicle passage was a major source of soil and plant disturbance. Effects on the soil ranged from slight surface scarification through to deepening of the active layer, thermal subsidence and gully erosion, e.g. at Chads Creek B-64. Crushing and uprooting of vegetation by vehicles was evident at all six wellsites. The damaging effects of vehicle movement on soils and vegetation were commonly more severe than the apparent chemical effects of drilling fluid spillage.

13) Sump infilling and site rehabilitation should be directed at enhancing natural processes of revegetation.

For example, ridging of infill materials along topographic contours over the sump and adjacent disturbed areas would provide a variety of microsites for establishment of plants. Restoration procedures which result in an arid, compacted fill surface hostile to plant growth (evident at Cape Fleetwood L-21 and Robert Harbour K-07) should be avoided.

Re-establishment of native arctic species via natural processes is slow; however, several plants exhibited a combination of desirable attributes. They were early colonizers of physically disturbed soils and were tolerant of saline conditions, e.g. *Alopecurus alpinus*, *Oxyria digyna*, *Luzula* spp. and *Papaver radicatum*. Stoloniferous species such as *Alopecurus alpinus* and *Luzula* spp. were prominent early colonizers in heavily disturbed soil immediately adjacent to sumps.

1 INTRODUCTION

A major environmental problem faced by the petroleum industry in northern Canada is the impact of their industrial wastes on natural systems. Problems develop initially during oil and gas exploration and recur throughout the exploitation and refining processes. At present, comparatively little is known about the environmental effects of drilling wastes. This adds to the already difficult problem of formulating appropriate guidelines for handling and disposal.

1.1 Drilling fluid composition and function:

Drilling fluids are commonly composed of water, and various solid mud components. Water forms the continuous phase of fluids used in the North.

One of the primary functions of drilling fluid is to remove rock cuttings or drilled solids from the bottom of the well hole. This is accomplished by pumping drilling fluid down the drill string to the bottom of the hole and drill bit. The fluid picks up cuttings and returns up the annulus outside the drill pipe to surface tanks and a treatment system. Cuttings are then removed and the fluid recirculated. Additional functions of drilling fluid are: cooling and lubrication, hole wall building, control of high sub-surface formation pressures, supporting the weight of the drill pipe and casing, and transmitting hydraulic horsepower to the bit. The average 3,049 m onshore northern well generates approximately 3.64 million litres (23,000 barrels) of waste fluid (Bryant and Hrudey 1976).

Major components of drilling mud recipes used in arctic drilling are listed below (a full list of the commoner mud components together with their functions is given by Bryant _et_ _al_. 1976):

Surface hole (less than 914.6 m - permafrost)
- bentonite (montmorillonite clay)
- potash (potassium chloride)
- X-C polymer (xanthan polymer)
- caustic soda (sodium hydroxide)

Intermediate hole (914.6 m to top of abnormal pressure zone)
- bentonite
- barite (barium sulphate)
- X-C polymer
- caustic soda

Bottom hole (over 2,439.0 m)
- barite
- bentonite
- lignosulphonates (ferrochrome organic compounds)
- caustic soda

These mud additives generally contain a variety of metal ions. Analyses by Imperial Oil Ltd., Canmar Drilling Ltd., and Panarctic Oils Ltd. indicate the following approximate levels of extractable metals in various drilling chemicals used in their northern operations:

Fe - as high as 47,600 mg/l
Zn - as high as 3,750 mg/l
Pb - as high as 1,650 mg/l
Cd - less than 0.5 mg/l up to 17 mg/l
Cr - 0.9 mg/l to 4.0 mg/l
Cu - 91 mg/l
Hg - 0.01 mg/l to 22 mg/l
As - 0.3 mg/l to 32 mg/l

The chemicals tested and extraction techniques used were not specified in this listing supplied by Environment Canada (Environmental Protection Service Memorandum, June 2, 1977).

Chemical composition of fresh drilling fluids can be considerably altered by natural additions of rock cuttings as the drill bit passes through different rock strata. Further chemical changes take place as the fluids age. The final waste product is a complex mix of compounds containing modified drilling muds, various organic bactericides used to control mud decomposition, and rig wash detergents.

Heavy metal concentrations in drilling fluids vary from well to well depending on subsurface conditions and the various mud additives used. Dissolved levels of cadmium and copper are generally below 0.05 mg/l in northern mud samples (Beak 1974a). Beak (1974a, 1974b) found dissolved concentrations of lead to be less than 0.25 mg/l in waste mud fluids. Bryant et al. (1974) found concentrations of this metal to be less than 0.12 mg/l in active sump samples.

Lignosulphonates and barites appear to be the most likely sources of zinc, chromium and iron in waste fluids. Chromium and iron concentrations in lignosulphonate (Peltex) are about 17,000 mg/kg and 40,000 mg/kg respectively (Beak 1974b). Iron content of barites can be as high as 39,000 mg/kg (Beak 1974b). Barites have also been identified as the principal source of abnormally high levels of mercury (10 ppm) and cadmium (20 ppm) noted in some waste fluids (Environmental Protection Service Memorandum, Environment Canada, November 23, 1977).

KCl is the major potassium and chloride additive, and caustic soda is the principal source of sodium.

1.2 Drilling fluid disposal:

Waste drilling fluids in the High Arctic are discharged into sumps for disposal. Land use permits issued under the Territorial Arctic Land Use Regulations specify that drilling fluids be contained completely in below ground sumps, and these sumps be infilled after their contents have frozen.

Some of the terrain and environmental problems associated with sumps have been described in detail by French (1978a, 1978b). They are summarized briefly here.

One set of problems relates to the thermal effects of sump fluids on the surrounding permafrost. Some melting of permafrost may occur around a sump, especially if the sump is left open over the summer or during a summer drilling operation. Serious problems can develop if the enclosing permafrost is ice-rich. Sumps may become considerably enlarged due to slumping of the walls.

In some cases, sump excavation exposes ice wedges or ice lenses in the permafrost. This raises the possibility of unfrozen fluids escaping by preferential thawing along ice wedges. The rate of gullying and headward erosion associated with this kind of melt can be rapid.

Large quantities of ground ice can lead to excavation problems. A sump is generally blasted with explosives and the loosened material removed by earth moving equipment. Presence of extensive ground ice in the permafrost; for example, ice wedges and massive ice structures, may reduce the effectiveness of the blast due to the different elastic properties of ice and mineral soil. Thus the initial sump may end up being smaller than planned, resulting in overflowing of drilling fluids and/or construction of an additional sump at a later date.

The most common group of problems relates to infilling of the sump and site restoration. The normal procedure in the High Arctic is for the original sump infill material, which is heaped to one side during sump construction, to be used as backfill. This restoration is undertaken in winter when heavy vehicle movement over frozen ground does relatively little damage. If the sump has been left open or drilling proceeded in the summer, infilling is not usually attempted until mid or late winter when sump fluids are frozen sufficiently to take the weight of the overburden. A doming of fill over the sump is usually practiced to compensate for subsidence. A number of specific problems have been documented by French (1978a):

1) The 'volcano effect' which occurs during sump infilling when drilling fluids are not sufficiently frozen. The frozen surface breaks under the weight of overburden, allowing unfrozen sump fluids to squeeze to the surface.

2) Infill subsidence and sump wall collapse. This generally results from incorporation of snow or ice in the infill (with melting in the summer) and/or seepage of water into the sump.

3) A lack of infill caused by melt-out of ice from infill material and a consequent loss of volume. The depression created leads to a standing water body over the sump which acts as a 'heat sink'.

4) Leakage of drilling fluids. This may occur if ice lenses in the sump walls melt or if the sump is too full on backfilling leading to seepage through the active layer.

5) Poor geographic location. For example, locating sumps in or immediately adjacent to watercourses where erosion of the sump walls (berms) and fluid release is likely.

6) Major terrain disturbance. This generally occurs during summer operations on well-vegetated, ice-rich tundra. It also happens when additional sumps have to be constructed or when technical problems are encountered down the hole.

1.3 Drilling fluid pollution:

Studies to date have mainly concentrated on drilling fluid seepage effects on ground and surface waters and general terrain disturbance associated with drilling operations. Drilling related terrain disturbance in the High and Low Arctic has been described thoroughly by French (1976, 1978a, 1978b).

Pollution of ground and surface waters by drilling fluid leakage from abandoned sumps in the Northwest Territories has been investigated by Hrudey _et_ _al_ (1976). These workers came to a number of conclusions based on an assessment of six sumps:

1) Current methods of sump reclamation commonly result in a depression over the sump due to slumping with formation of surface pools.

2) Natural pools within a few hundred metres of sumps are commonly contaminated by drilling mud chemicals. Adjacent lakes and streams, however, are generally pollutant free.

3) Groundwater within 7.6 m - 0.2 m of sumps is commonly polluted by mud chemicals indicating that leaching has occurred. However, lack of a significant hydraulic gradient generally prevents any great movement of the limited volumes of sump fluid leachate.

4) Areas adjacent to mud handling equipment are subject to spills covering areas from a few square metres to several hundred.

5) Fluid quantities leaking from most sumps result in a minor degree of water pollution. However, if persistent and highly toxic compounds were placed in a sump they would occur in this limited seepage. These materials, in relatively low concentrations, could create a long term environmental hazard due to cumulative properties within ecosystems.

6) With efficient reclamation procedures, including a sump mound, most drilling fluids remain frozen in the permafrost.

Very little information has been assembled thus far detailing the effect of sump problems or of problem-free sump construction and site restoration on soils and vegetation in the Canadian Arctic. Bryant et al (1976) made the general observation that, "Contamination of the environment by heavy metals (from sump fluids) can affect living organisms in the following ways:

1) By lethal or sublethal effects which cause disruptions in biological systems of the individual organisms.

2) By inducing changes in species composition of communities in the general area of effluent discharge which can lead to further ecological disruption.

3) Accumulation and concentration of heavy metals in the food chain can cause lethal concentrations to build up in higher trophic forms resulting in a greater spatial distribution of metals, thus, contamination of previously unaffected animals."

However, quantification of drilling fluid pollution impacts on terrestrial arctic environments is largely lacking.

Bryant et al (1976) noted that, except for drill cuttings piles, wellsites seem to be able to revegetate naturally, although slowly because of the short growing season and consequent slow growth rates in the Arctic.

Bohun (1974) observed no vegetation on drill cuttings piles and suggested that this was due to lack of available nutrients rather than toxicity. Absence of vegetation has also been noted at the edges of sump ponds (Bohun 1974) and across the entire area of some drilling sites. Bohun (1974), however, observed no long-term toxic effects on terrestrial vegetation associated with sump ponds.

Some plant community responses to disturbances, such as vehicle passage along seismic lines, have been documented for the High Arctic (Babb and Bliss 1974). Jones *et al* (1976) has described the heavy metal contents of some tundra plants.

2 THE ALUR SUMP PROJECT

The main objective of the ALUR sump project is to provide environmental and geotechnical information related to the construction, use and subsequent restoration of sumps in a variety of permafrost and terrain situations. A secondary objective is to assess alternate methods of disposing of waste drilling fluids, particularly direct spillage on the tundra. A third, long-term objective is to evaluate effectiveness of the Arctic Land Use Regulations as they relate to the drilling of oil and gas wells in permafrost and the disposal of drilling fluids.

There are four phases to the project.

The first phase was completed during the summers of 1976 and 1977. Old and active wellsites in the High and Low Arctic, of varying ages and located in differing terrain and permafrost environments were surveyed. The objectives were to identify reasons for the failure or success of sumps, to develop case histories and documentation of sump problems, and to identify localities where drilling without a sump may have been preferable. The results of this work were reported by French (1978a).

A second phase of the project, completed during the winter of 1976-1977, consisted of instrumenting two sumps in order that the thermal and geomorphic changes associated with operation, restoration and subsequent abandonment of the sumps could be monitored. Of especial interest were (a) the influence of sump fluids upon permafrost thermal regimes, (b) the determination of whether or not sump fluids freeze in situ, plus the time period involved, and (c) the nature and extent of any thermokarst activity that might develop. One sump, at the Panarctic Oils Ltd. Bent Horn I-01 wellsite on Cameron Island, was instrumented in November 1976. A second, the Gulf Canada Ltd. Ogruknang M-31 sump in the Caribou Hills, Mackenzie Delta, was instrumented in April 1977. Monitoring of these two sites was continued into the summer of 1978. Results of this phase of the project have been detailed by French and Smith (1979).

A third phase involved development of numerical simulation models to illustrate the thermal effects of sump fluids on the enclosing permafrost. Models generated were tested against field data obtained from the instrumented sites (French and Smith 1979).

A fourth phase of the project involved a consideration of the toxicity and effects on vegetation of waste drilling fluids. A number of old wellsites in the High Arctic islands and the Mackenzie Delta were visited during the summer of 1977 to investigate the effects of leakage of drilling fluids, and to develop case histories. The survey of old wellsites in the Mackenzie Delta was continued in 1978.

This report deals only with the fourth phase of the project, specifically a survey of six High Arctic wellsites visited in mid-July, 1977. These sites, located on Cameron and Melville Islands, were all drilled by Panarctic Oils Ltd. A later report will detail results of the sump studies undertaken in the Mackenzie Delta.

2.1 Objectives of the High Arctic sump survey:

The survey of abandoned drilling sumps in the High Arctic was:

1) To document alterations in soils and vegetation coincident with disposal of drilling wastes in sumps.
2) To correlate changes in vegetation to physical disturbance of the terrain, important abiotic and topographic variables of the site, and particularly to the toxicological characteristics of drilling fluids.
3) To identify, where possible, causal agents of toxicity in the drilling wastes and determine their fate after release of drilling fluids.

The overall purpose of the research was to provide information for management to minimize the damaging effects of drilling waste disposal and to enhance the recovery rate of affected terrain and vegetation.

3 GEOGRAPHY AND VEGETATION OF STUDY REGION

The area covered by the study included Melville and Cameron Islands located in the centre of the Canadian Arctic Archipelago (Figs. 1, 1a and 1b).

The climate of this region is modified by the sea except in the interiors of larger islands, such as Melville Island, where a more continental climate prevails. The cooling influence of the largely frozen ocean plus the high latitude results in low growing season temperatures. Precipitation is slight (5-20 cm/year).

Most of the Canadian Arctic Archipelago is composed of uplifted Silurian through Tertiary sediments (Geological Survey of Canada 1969). Quaternary alluvium and drift of the Arctic Coastal Plain occurs along the north-west margin.

High Arctic soil characteristics are a result of frost action and the presence of permafrost which restricts drainage and affects the vertical movement of soil water. Salinization, wind erosion and, especially, the sparseness of vegetation cover as a source of organic matter are also important factors (Tedrow 1966, 1968). A high frequency of limestone or other carbonate rich sediments is responsible for the predominance of alkaline soils in many places.

Most of the soils in the region are little more than sediments or colluvium weakly weathered *in situ*. Soil profiles are poorly developed and parent materials can exercise strong control over the character of plant communities.

The sparse plant cover in much of the High Arctic plays only a very minor role in governing geomorphic processes. Watercourses formed by the annual spring snowmelt are typically choked with fine materials from wind and sheet erosion and from frequent mud slumps along their banks.

Polunin's (1960) term 'polar desert' is applicable in most of the High Arctic, except in the few favourable sites where tundra meadow develops. Where relief is low, for example on Cameron Island, a very narrow range of habitat variation accommodates a correspondingly low species diversity. Community segregation is often weak because interspecific effects in sparsely vegetated areas are slight (Babb and Bliss 1974). A number of species can occur in many loose associations depending on abiotic variables. Micropattern in the High Arctic vegetation may be highly variable, expecially in areas of hummocky microrelief and frost fissuring.

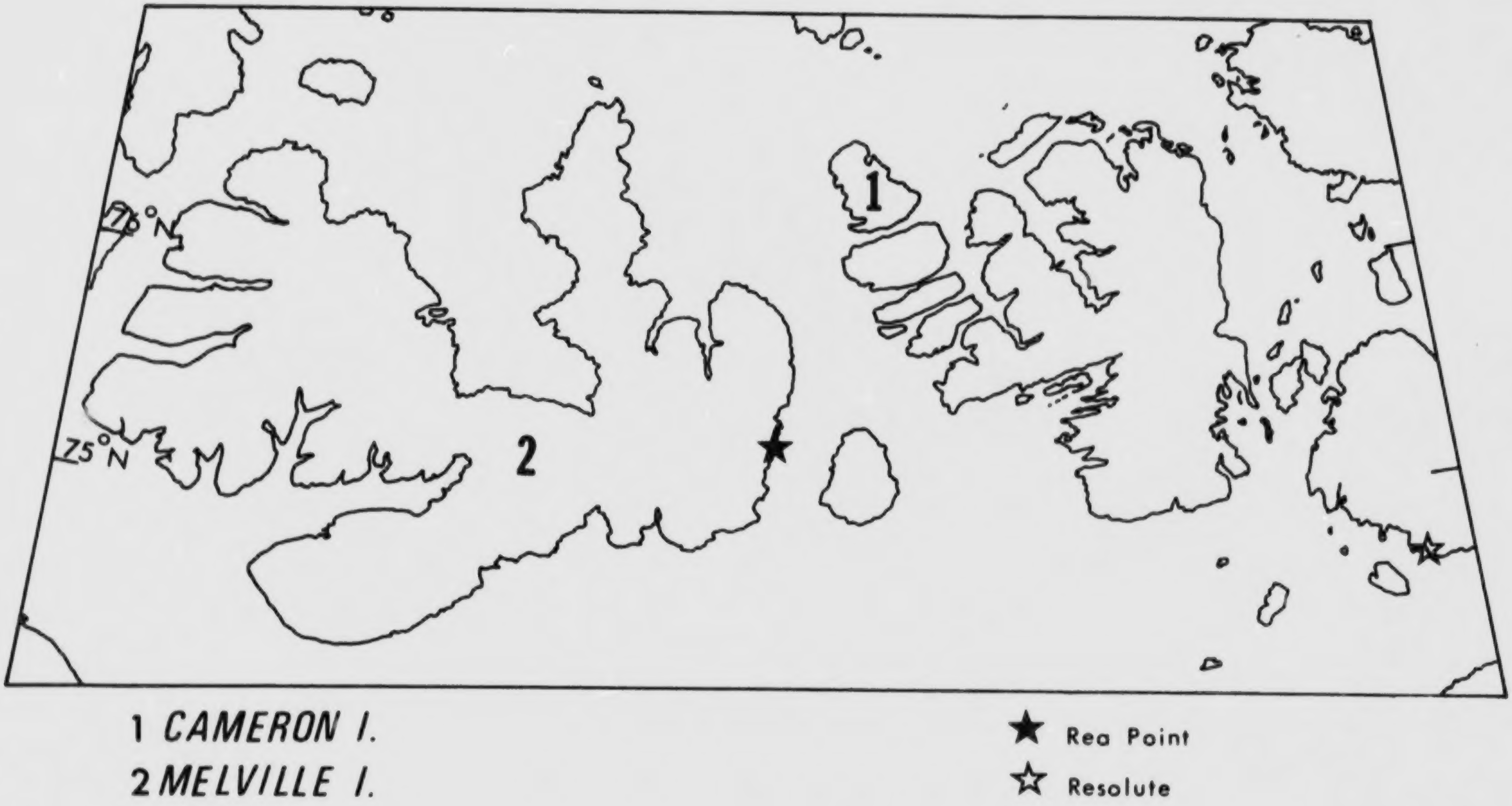

1
2
76°N
75°N
1 CAMERON I.
2 MELVILLE I.
★ Rea Point
☆ Resolute

Figure 1. Map of study region

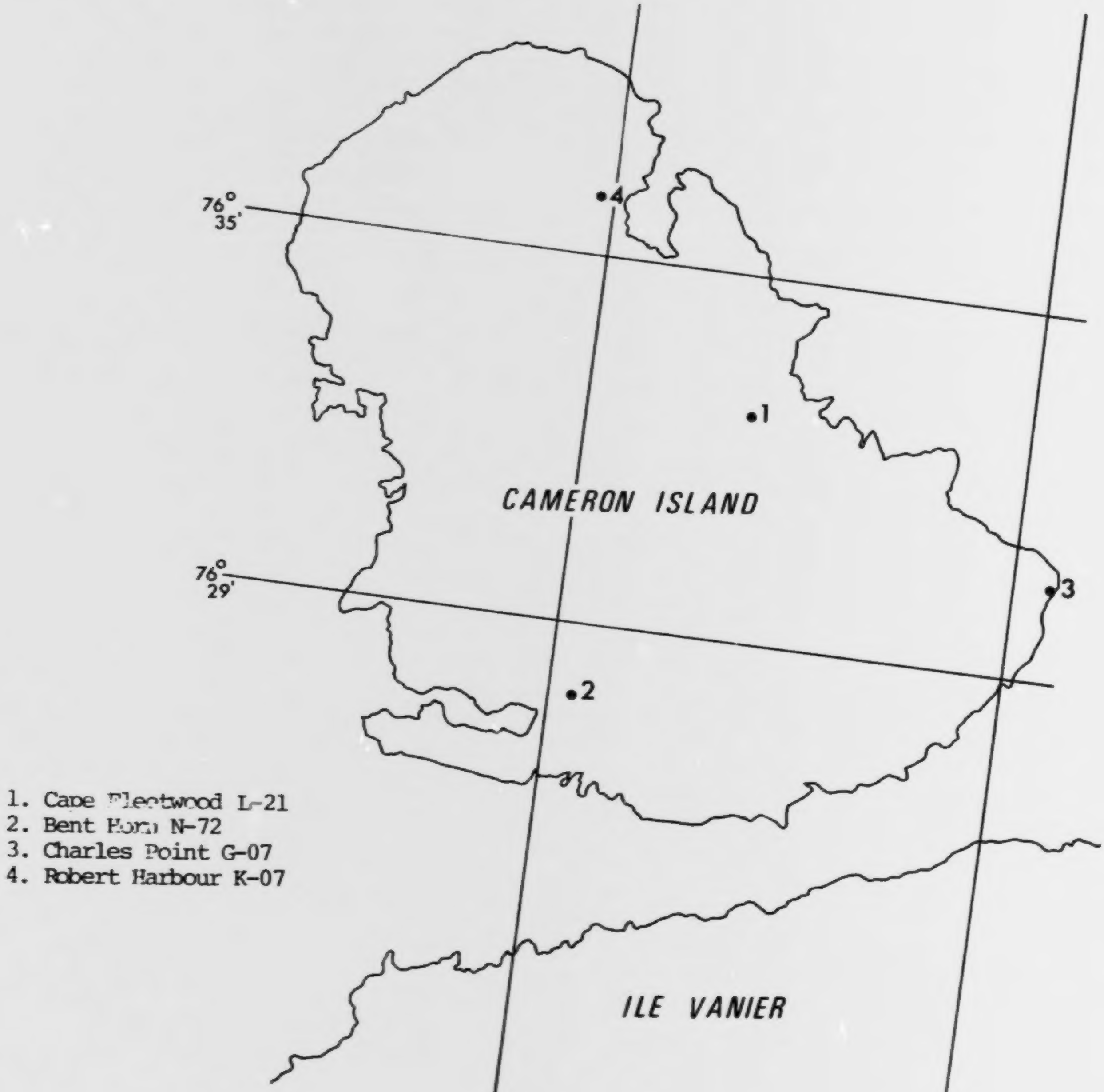

76° 35'
76° 29'
•4
•1
CAMERON ISLAND
•3
•2
1. Cape Fleetwood L-21
2. Bent Horn N-72
3. Charles Point G-07
4. Robert Harbour K-07
ILE VANIER
104°
103°

Figure 1a. Sampled wellsites on Cameron Island, N.W.T.

5. Apollo C-73
6. Chad's Creek B-64

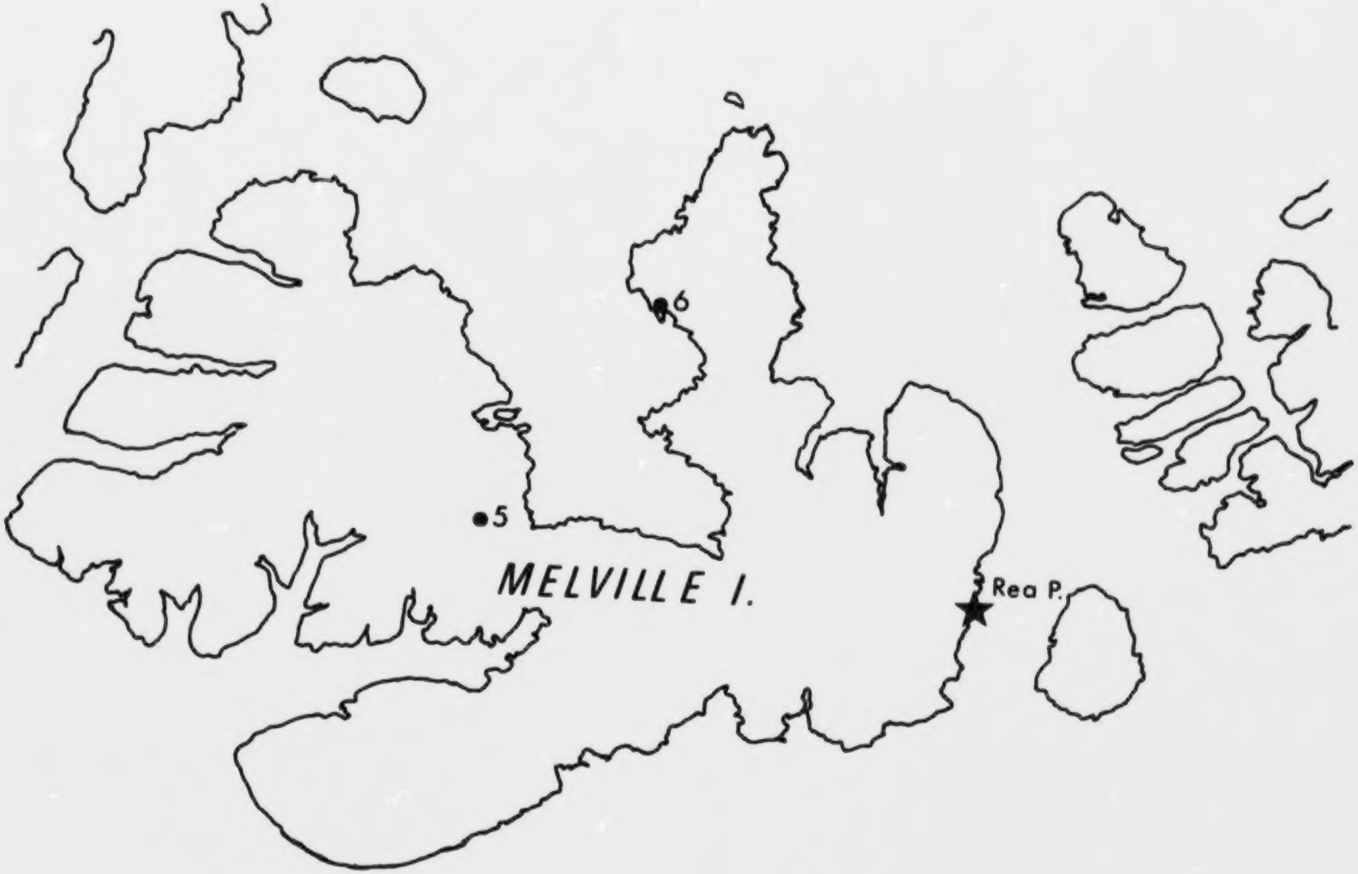

6
5
MELVILLE I.
Rea P.

Figure 1b. Sampled wellsites on Melville Island, N.W.T.

Important species in the low-lying portions of Melville and Cameron Islands include *Alopecurus alpinus* J.E. Smith, *Luzula nivalis* (Laest.) Beurl., *Luzula confusa* Lindebl., *Saxifraga* spp., *Potentilla* spp. and *Papaver radicatum* Rottb. *Salix* spp. are important in some areas but are microclimatically confined to warmer sites. *Salix* spp. are infrequent on Cameron Island. Crustose lichens are important in most locations comprising approximately 10% of total ground cover and locally 60% cover or more. Mosses dominate the tundra meadow sites but are relatively unimportant in the drier habitats. *Ditrichum flexicaule* (Schwaegr.) Hampe is among the more commonly found mosses in dry sites.

4 SURVEY METHODS

4.1 Plot design and mapping:

Sampling at each wellsite was from an 6,400 m^2 grid subdivided into 400 m^2 blocks. The grid was laid out downslope of the drilling sump with the baseline parallel to and approximately 510 m from the sump berm. Coordinates on the grid were numbered and sampling was completed at these points (Fig. 2). Sample area placement included a gradient of vegetation and soil disruption, ranging from highly disturbed to natural or near-natural. This condition was met at all six sites.

Brief descriptive notes and diagrams were prepared at each site to record position of the sump, the sample area, and major topographic features.

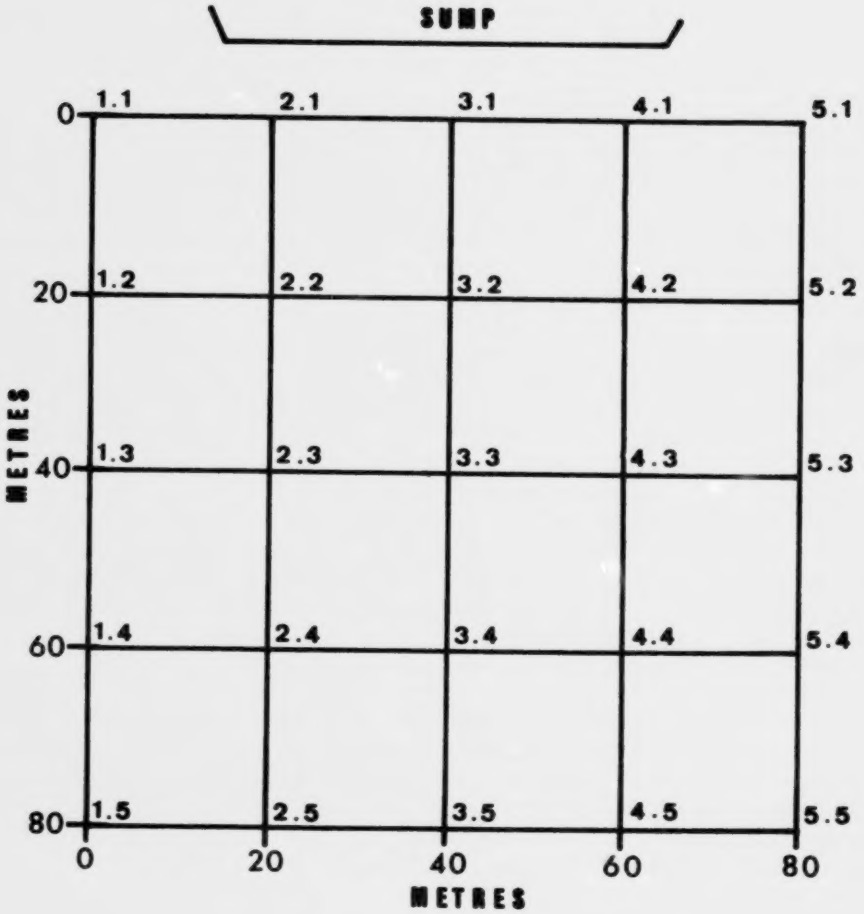
Topographic measurements in decimetres were taken at each coordinate using a hand-held Abney level. Elevation between coordinates was also measured in gullies wherever these were present. This information was used to develop contour maps of the sample areas. In these analyses, the point of lowest elevation in each grid was designated zero and elevation at other points was expressed relative to this zero base. The mapping was implemented on an IBM 370/155 computer using a Calcomp plotter.

4.2 Field sampling and laboratory analysis:

Soil was sampled from pits dug at each grid coordinate at depths (where possible) of 0-5 cm and 15-20 cm. A third sample was taken of the basal 5 cm of the active layer. Soil at each depth was removed from the four sides of the pit and made into one composite sample. Other soil measures taken included active layer depth and descriptions of organic matter content, stoniness and texture.

At sites where spillage of drilling fluids had occurred, surface deposits were collected in areas of maximum mud accumulation. Laboratory processing of these samples followed the same procedures as described for soil.

The soil samples were analysed for acetate-extractable potassium, sodium, barium, zinc, copper, lead, chromium, cadmium, manganese and chloride following oven-drying to constant weight at 50°C, sieving through a 20-mesh screen and thorough mixing. Levels of the cations, in a 1.0 N ammonium acetate extract, were measured using a Perkin-Elmer Model 303 atomic absorption spectrophotometer and standard procedures (Perkin-Elmer Corp. 1971). Chloride in the acetate extracts was measured by the thiocyanate method using a Technicon autoanalyzer (Technicon Instruments Corp. 1976) following precipitation of tannins with silver nitrate.


SUMP
1.1
2.1
3.1
4.1
5.1
1.2
2.2
3.2
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2.3
3.3
4.3
5.3
1.4
2.4
3.4
4.4
5.4
1.5
2.5
3.5
4.5
5.5
0
20
40
60
80
METRES
0
20
40
60
80
METRES

Figure 2. Sample grid design.

Soil pH was determined using a 20 g aliquot of each oven-dry soil sample. The soil was thoroughly wetted with distilled water and pH measured in the soil-water slurry using a Portomatic pH meter with a combination electrode.

Water samples were collected at some sites in undisturbed areas, from ponds on the sump fill and from ponds and drainageways located downslope from the sump. These samples were tested for water-soluble concentrations of potassium, sodium, zinc, copper, lead, chromium, cadmium, manganese and chloride. Atomic absorption and autoanalyzer techniques were used to analyze the water samples.

Vegetation was sampled at each grid coordinate by recording presence-absence of plant species and bare soil in a series of four-blocked, contiguous 50 cm^2 quadrats. The quadrat blocks were all located in the same position with respect to each coordinate. Voucher specimens were taken of species encountered during the sampling. Plant identifications were verified by W.J. Cody and G.A. Mulligan, Biosystematics Research Institute, Agriculture Canada, Ottawa, and R.R. Ireland and I.M. Brodo, Museum of Natural Sciences, National Museum, Ottawa.

Whole plant samples of visually dominant elements of the vegetation were collected at each coordinate for chemical analysis. These samples were oven-dried at 50°C to constant weight then ground in a Wiley mill and passed through a 20-mesh sieve. Concentrations of potassium, sodium, zinc, copper, lead and chromium were measured in acid digests of the samples. The procedure of Lindner and Hartley (1942), modified by addition of 30% H_2O_2, was used in the digestions. Chloride was measured in aqueous solutions following extraction with hot water. Chloride levels were assessed using a Technicon autoanalyzer and the thiocyanate method (Technicon Instruments Corp. 1979). Concentrations of the metal ions were measured using a Perkin-Elmer model 303 atomic absorption spectrophotometer and standard procedures (Perkin-Elmer Corp. 1971).

In addition to the grid sampling, vegetation and soils were also measured in two undisturbed areas at each site located approximately one kilometre from the well sump. Sampling was identical to that at grid coordinates and chemical analysis of the natural area samples followed the procedures already outlined.

4.3 Data analysis:

Topographical maps were drawn for each site on a CALCOMP plotter using computer mapping program SCIPI3 (on file at the University of Guelph) and the elevation data. A three-dimensional topographical view of each site was also plotted using a sub-routine built into SCIPI3.

Active layer depth downslope of the sump is presented as a series of profiles measured along each sampling line on the grid. Mean active layer depths were also calculated at various downslope distances and were represented graphically.

Mean extractable levels of each ion and pH at the three soil depths were calculated at each 20 m interval from 5-85 m downslope from the sump. One-way analysis of variance with a standard F test was used to test for significant differences between these means. Sample grid means and anova results were tabulated for each site together with mean ion concentrations and pH in undisturbed soil.

Two-dimensional contour maps of the soil pH and ion distributions at each site were drawn using program SCIPI3. Maps describing the distribution of each ion at the three soil depths were constructed from the concentration data measured at sample grid coordinates. Maps of pH were constructed similarly. To simplify the maps, the ion concentration and pH data were divided arbitrarily into classes and these classes were plotted together with surface topographical data.

Levels of cations and chloride in standing and flowing water at each wellsite are presented as raw data. Collection of replicate water samples was not feasible, thus mean values could not be calculated.

Percentage frequencies of plant species were calculated at each 20 m interval from 5-85 m downslope from the sump using the species incidence data. These results were tabulated along with frequencies of species recorded in the undisturbed areas.

At each site a vegetation disturbance index (VDI) was calculated for the undisturbed area and downslope distances of 5, 25, 45, 65 and 85 m from the sump. VDI was derived by expressing the sum of observed occurrences of all species in an area as a percentage of the total possible number of occurrences if all the species recorded at the site occurred in that area with a frequency of 100%. The value calculated was a composite measure of the effects of disturbance on species incidence and richness of the vegetation.

Vegetation disturbance was also evaluated by ordination of sample grid coordinates using species incidence (presence/absence) as attributes. Data from the ordinations were used to map patterns of disturbance in the plant communities at each site. Ordinations were completed on an IBM 370/155 computer using a reciprocal averaging technique contained in the ORDIFLEX program package from Cornell University, New York (Gauch 1977).

ORDIFLEX derives reciprocal average ordinations through a successive series of iterations. First, each species is assigned an arbitrary score value by the program. The initial iteration then uses weighted averages (Gauch 1977) to obtain sample scores. The second iteration uses the same procedure as the first but, beginning with sample scores produced in the first iteration, obtains new species scores. This iterative process is continued until close to 100% of the variability in the data has been extracted.

Species scores are scaled from 0-100 at each iteration to prevent the numbers from drifting into a very small range. The sample scores are also scaled from 0-100. Hill (1973) showed that scores thus defined will converge to a unique solution, and that this solution is not affected by the initial arbitrary species scores. The contraction in range of species or sample scores in one iteration (after convergence has been reached) is the eigenvalue upon which ordination is based (Hill 1973). Reciprocal averaging has species-sample duality, both are ordinated simultaneously.

Completion of successive iterations results in extraction of one axis accounting for a certain percentage of variability in the data. This first axis proportionally extracts the greatest percentage of variability and describes the most important gradient of variation. Having extracted one axis, it is possible to extract a second by correcting for the first. This second axis essentially describes the second most important gradient of vegetation variation. The axes extracted have eigenvalues in a decreasing sequence (Hill 1973 gives the details). Only the first two axes were used to map disturbance patterns in the High Arctic vegetation.

Visual observations and various computational techniques indicated that the most important gradient (A) in the vegetation at each site was the change in species richness and frequency downslope from highly disturbed areas close to the sump to undisturbed situations. Across-slope variation in vegetation composition and species frequency with intensity of disturbance was the second most important gradient (B). Vegetation mapping was completed using the scores assigned by ORDIFLEX to each sample grid coordinate on the first axis (gradient A) and second axis (gradient B) in combination. The calculated community disturbance values (CDV) described the composite effect of disturbance on species richness and incidence at the grid sample points (akin to defining a VDI value for each grid coordinate).

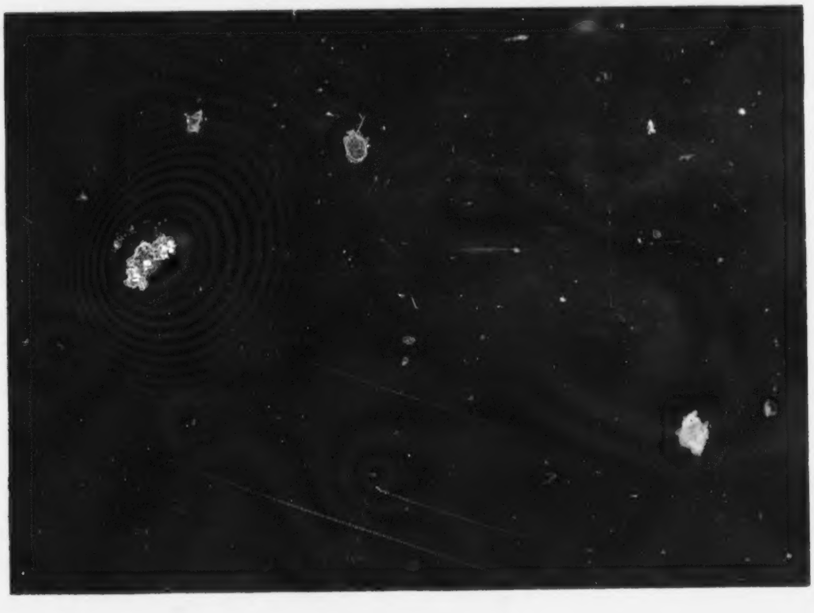
Sample point scores on the second ordination axis were corrected to account for the influence of the first axis using a scaling factor supplied by ORDIFLEX. For each grid sample point, the uncorrected first axis score was then added to the corrected score on the second axis to give the composite CD value. In all cases those sample grid points with the highest CD values were located in the most disturbed areas containing a small number of species occurring at low frequencies. Grid coordinates with no plant cover (not included in the ordinations) were assigned the highest CD values (in all cases greater than the highest ORDIFLEX derived CDV).

The CD data were analyzed using program SCIP13 to give computer drawn CDV contour maps. A final step involved arbitrarily dividing the full range of CD values into a maximum of four classes for each site (I, II, III and IV) in order of increasing vegetation community disturbance (CDV). These classes are mapped along with surface topography for each site in the survey results section.

Mean total concentrations of cations and chloride in the dominant elements of the vegetation were calculated at each 20 m interval from 5-85 m downslope of the sump and in the undisturbed areas. No statistical tests were applied to these data because for any one species the base at each site was too limited. Mean concentrations of some major ions in the plants are tabulated in the survey results section.

Plate 1.

Air view of Cape Fleetwood L-21 showing surface pond in depressed sump infill, sheetwash of fill overburden downslope, and proximity of site to a watercourse.



Breach in sump berm at Cape Fleetwood L-21 with sheetwash of sand fill downslope.

5 WELLSITE SURVEY RESULTS

5.1 Cape Fleetwood L-21

5.1.1 Site description and well history:

Cape Fleetwood L-21 (76° 30' 47.80"N 130° 40' 37.00"W) is located on moderately dissected semi-polar desert terrain on the east coast of Cameron Island (Fig. 1a). The well was spudded on September 23, 1974 and completed on December 9, 1974. Final drilling depth was 3,515 m.

A gel-polymer mud system was employed in the drilling (Table 1). Total quantity of mud solids used (ca. 70,680 kg) was low relative to other deeper wells surveyed in the High Arctic. No liquid components other than freshwater were added to the mud system.

Waste drilling fluids were discharged to a sump approximately 46 m x 46 m x 4 m excavated in sandy soil with a low silt and stone content. The sump was located on slightly sloping terrain at the edge of a small plateau. Slope angles of 6° or more occurred immediately downslope of the sump berm (Fig. 3). Sump infill material was sand derived from the original excavation. There was no history of sump problems during either drilling or infilling operations.

When Cape Fleetwood L-21 was visited in July, 1977 some slumping of the sump infill was evident. Standing water was present in one corner of the sump close to the downslope berm (Plate 1). Gullying had developed in the infill but drilling mud was not seen at the surface or exposed in the gullies. The sump berm immediately above the sample grid was cut by gullies in two places (Plate 1) and sand infill material had been carried approximately 40-50 m downslope by meltwater. Infill material was also noted at some distance from the sump in two natural downslope gullies. These connected with a major watercourse approximately 2 km from the site.

Plant cover (ca. 20%-30% in undisturbed areas) was virtually absent in many areas at 5-40 m downslope from the sump. The main cause of vegetation disturbance appeared to be burial by infill material sheet-washed from the sump. Evidence of chemical contamination, such as surface salt deposits, or of mechanical scarification by heavy vehicles was not observed in the sample grid.

Sparse recolonization of some areas buried by sump infill was occurring. The main colonizers were *Alopecurus alpinus*, *Luzula* spp., *Oxyria digyna* (L.) Hill and *Papaver radicatum*.

Table 1 Total quantities of solids discharged to drilling sump at Cape Fleetwood L-21, Cameron Island

Product	Description	Quantity (kg)
	Barium carbonate	45,364
	Salt gel	12,182
Kelzan X-C polymer	Xanthan gum	7,682
Caustic soda	Sodium hydroxide	2,318
Lime	Calcium hydroxide	589
	Sawdust	166 sacks
	Sodium bichromate	841
	Sodium bicarbonate	727
	Chrome alum	977
TOTAL		70,680 + 166 sacks

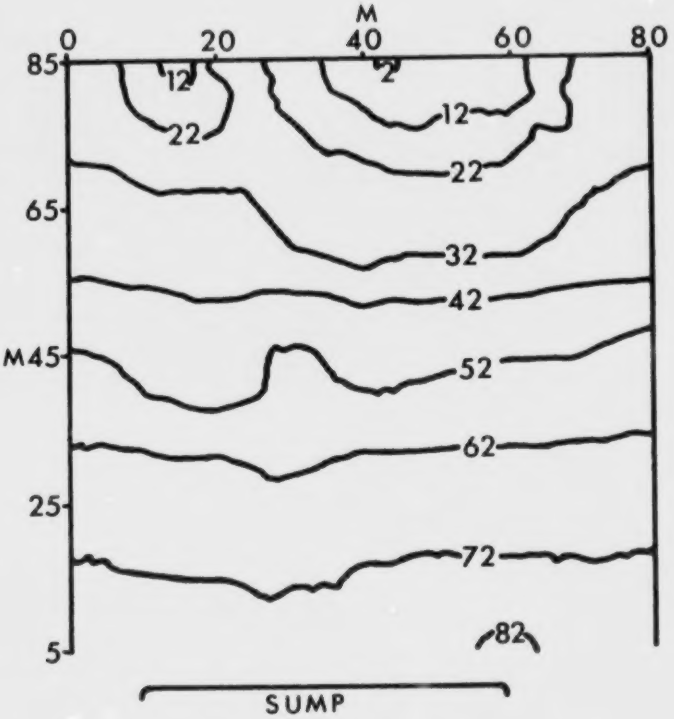

M
0
20
40
60
80
85
65
M45
25
5
12
2
12
22
22
32
42
52
62
72
82
SUMP

Figure 3. Topography at Cape Fleetwood L-21
(contour intervals in dm).

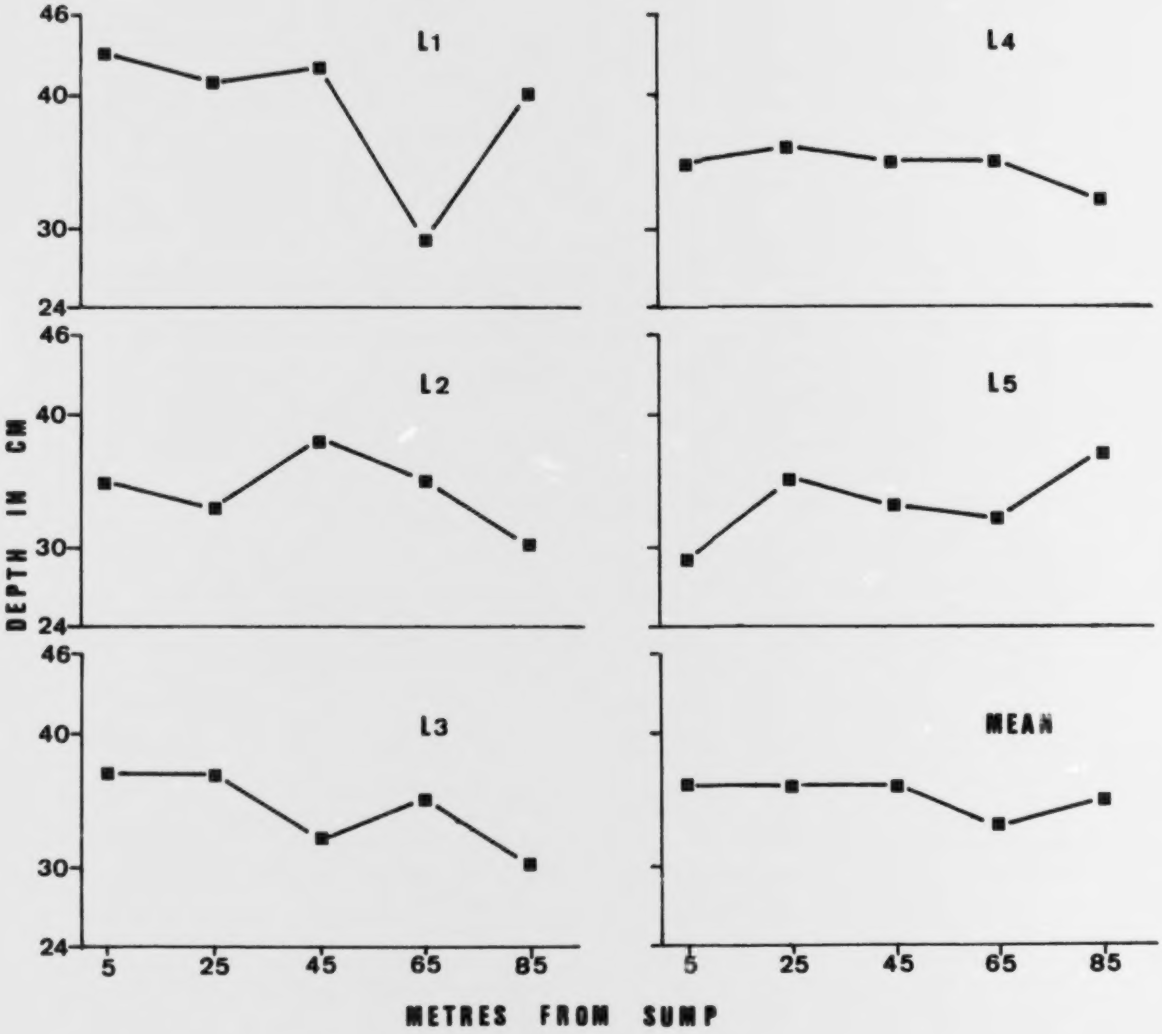


Figure 4. Active layer depth at Cape Fleetwood L-21 (measured on July 13, 1977).

5.1.2 Active layer depth:

Little variation in active layer depth occurred downslope of the sump at Cape Fleetwood L-21. The frost-table in mid-July was closest to the soil surface at 5 m from the sump on line 5 (Fig. 4) and at 65 m on line 1 (the position of grid lines 1-5 in relation to the sump are shown in Figure 2). There was no evidence of thermokarst development or thermal erosion of permafrost causing increases in active layer depth close to the sump. The only apparent thermal effects of drilling at this site were subsidence of sump infill.

5.1.3 Soil ion content:

Levels of ammonium acetate-extractable potassium in soil downslope of the sump were not significantly different from background levels (Table 2). There was some evidence of slightly elevated potassium concentrations between 5 m and 10 m from the sump at soil depths of 0-20 cm (Fig. 5), but this trend was inconclusive. Elevated levels at 85 m from the sump in the mid and basal portions of the active layer (Fig. 5) reflected build-up of potassium leached from the surrounding mineral soil at the base of a deep, natural gully.

Mean concentrations of extractable soil sodium are reported in Table 2. Sodium levels diminished downslope of the sump at all soil depths; however, this trend was only significant at depths ranging from 15 cm to the base of the active layer. High levels of sodium were present throughout the active layer at 5 m from the sump. Mean sodium concentrations in this area were 1,824% of background levels.

Sodium levels at 0-20 cm soil depth were greater than background throughout the sample grid indicating that widespread downslope movement of this cation had taken place. High accumulations of sodium, however, only occurred between 5 and 10 m from the sump and were quite restricted in lateral extent (Fig. 6).

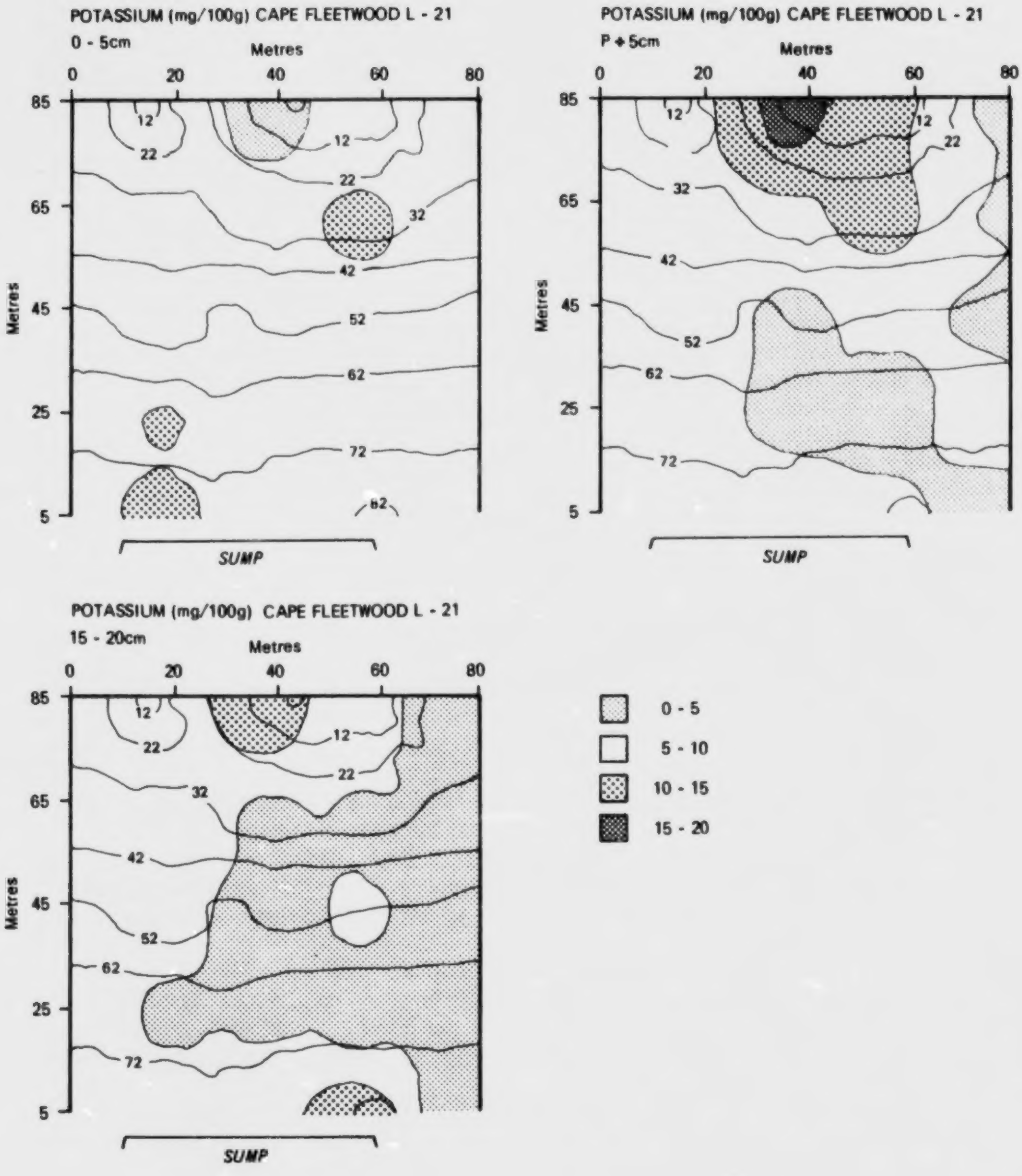
Elevated levels at 0-5 cm soil depth coincided with the head of a natural gully, an extension of which crossed the sump infill. High sodium levels at 15-20 cm depth occurred in an area of extensive sand overburden sheet-washed from the sump.

Sodium concentrations (mg/100 g) measured approximately 40 m from the sump in downslope gullies were 26.3 at 0-5 cm depth; 37.2 at 15-20 cm depth; and, 37.2 at 5 cm above the frost-table. These levels (ca. 2,700%-3,300% of background) were much higher than in the surrounding soils and showed that sodium-rich sump materials were concentrated in natural drainageways.

Table 2. Mean concentrations (with standard errors) of extractable cations and chloride in soil at Cape Fleetwood L-21

Soil depth (cm)	Concentration (mg/100 g) at distance from sump (m)					
	5	25	45	65	85	UD
POTASSIUM						
0 - 5	8.2 ± 1.1	8.2 ± 0.9	7.5 ± 0.7	8.5 ± 1.2	6.4 ± 1.0	9.2 ± 0.6
15 - 20	8.3 ± 1.8	4.3 ± 1.0	5.6 ± 1.0	5.6 ± 1.0	7.6 ± 1.6	8.1 ± 0.5
P + 5	6.8 ± 0.9	5.2 ± 0.9	5.9 ± 1.0	8.6 ± 1.3	9.8 ± 2.1	8.3 ± 0.5
SODIUM						
0 - 5	18.5 ± 9.7	9.0 ± 1.9	6.6 ± 1.9	6.9 ± 3.2	4.8 ± 3.4	0.97 ± 0.03
15 - 20 *	21.5 ± 8.1	10.8 ± 5.5	0.9 ± 0.1	3.5 ± 1.9	2.5 ± 0.8	1.3 ± 0.2
P + 5 *	19.1 ± 4.6	10.9 ± 4.9	5.0 ± 3.7	1.5 ± 0.4	1.6 ± 0.3	0.97 ± 0.03
BARIUM						
0 - 5	0.84 ± 0.20	0.30 ± 0.03	0.33 ± 0.04	0.54 ± 0.20	0.45 ± 0.10	0.38 ± 0.04
15 - 20	0.74 ± 0.40	0.23 ± 0.05	0.27 ± 0.06	0.22 ± 0.02	0.33 ± 0.10	0.42 ± 0.02
P + 5	0.38 ± 0.20	0.19 ± 0.06	0.24 ± 0.08	0.32 ± 0.07	0.43 ± 0.20	0.41 ± 0.02
MANGANESE						
0 - 5	0.18 ± 0.06	0.30 ± 0.03	0.27 ± 0.03	0.69 ± 0.36	0.43 ± 0.10	0.40 ± 0.20
15 - 20	0.15 ± 0.07	0.07 ± 0.01	0.05 ± 0.01	0.22 ± 0.16	0.08 ± 0.01	0.30 ± 0.10
P + 5	0.08 ± 0.01	0.06 ± 0.01	0.04 ± 0.07	0.22 ± 0.14	0.14 ± 0.05	0.10 ± 0.005
CHLORIDE						
0 - 5 *	98 ± 4	106 ± 4	95 ± 1	95 ± 1	90 ± 4	90 ± 1
15 - 20 *	104 ± 4	102 ± 3	94 ± 1	93 ± 1	92 ± 1	90 ± 1
P + 5	109 ± 4	128 ± 22	94 ± 1	93 ± 1	98 ± 5	89 ± 1

*anova significant at $P_{0.05}$ level UD - undisturbed area P - frost-table


POTASSIUM (mg/100g) CAPE FLEETWOOD L - 21
0 - 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
12
22
12
22
32
42
52
62
72
62
SUMP
POTASSIUM (mg/100g) CAPE FLEETWOOD L - 21
P + 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
12
12
22
32
42
52
62
72
SUMP
POTASSIUM (mg/100g) CAPE FLEETWOOD L - 21
15 - 20cm
Metres
0
20
40
60
80
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65
45
25
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Metres
12
22
12
22
32
42
52
62
72
SUMP
0 - 5
5 - 10
10 - 15
15 - 20

Figure 5. Potassium concentrations in soil at Cape Fleetwood L-21.

Contour intervals are in dm and P+5 cm
-- 5 cm above the frost-table.

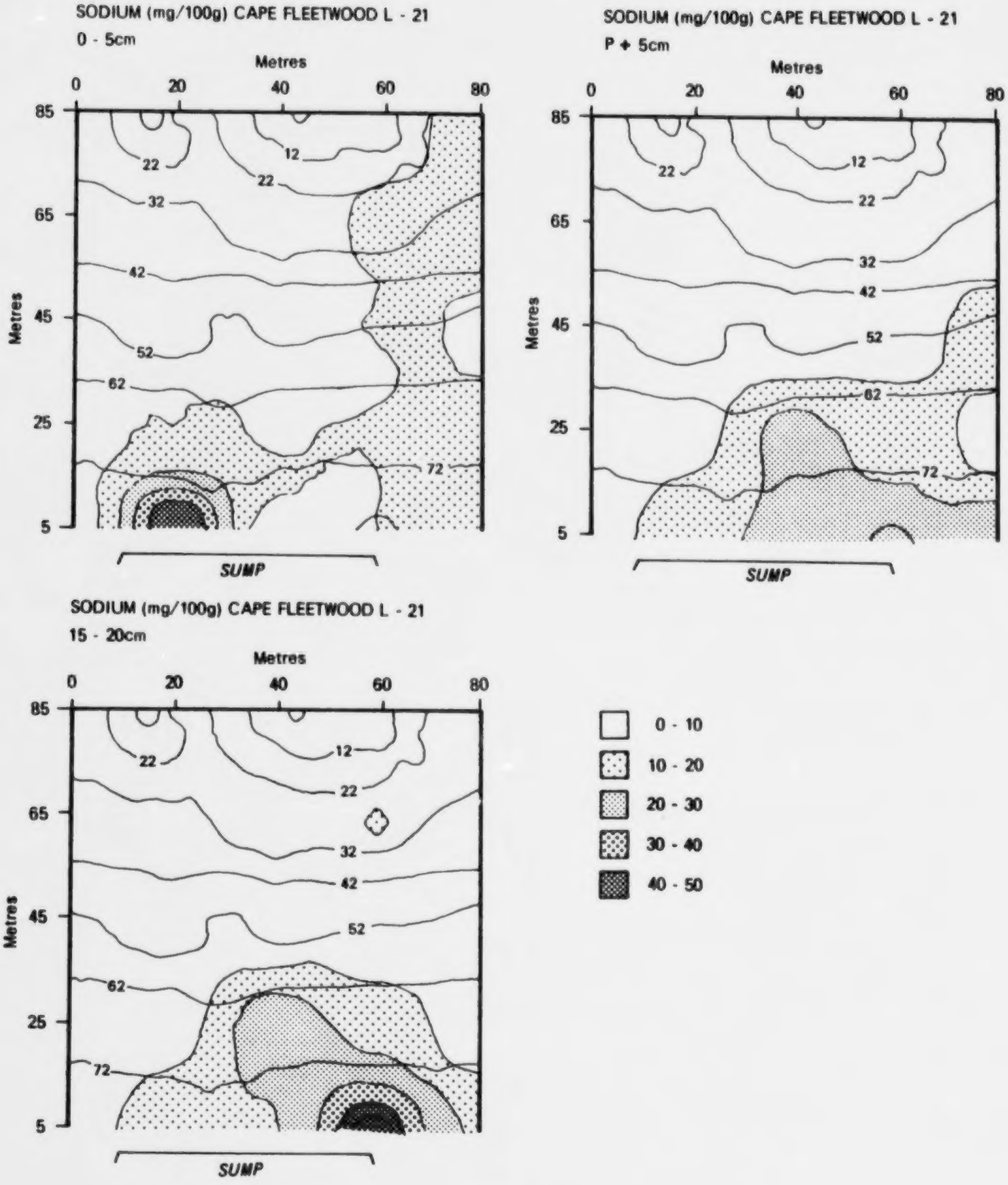

SODIUM (mg/100g) CAPE FLEETWOOD L - 21
0 - 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
22
12
22
32
42
52
62
72
SUMP
SODIUM (mg/100g) CAPE FLEETWOOD L - 21
P + 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
22
12
22
32
42
52
62
72
SUMP
SODIUM (mg/100g) CAPE FLEETWOOD L - 21
15 - 20cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
22
12
22
32
42
52
62
72
SUMP
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50

Figure 6. Sodium concentrations in soil at Cape Fleetwood L-21.

Contour intervals are in dm and P+5 cm
-- 5 cm above the frost-table.

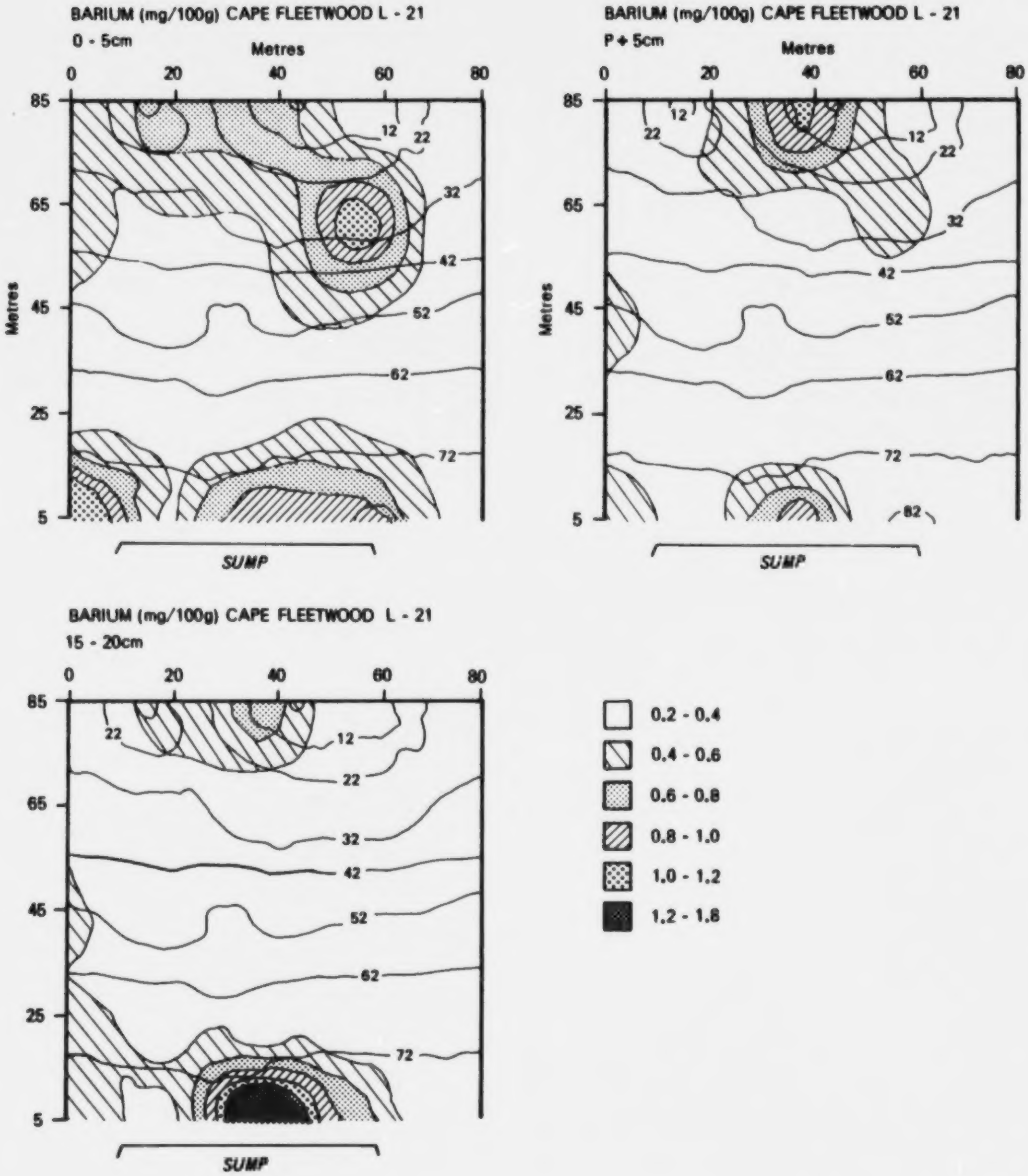

BARIUM (mg/100g) CAPE FLEETWOOD L - 21
0 - 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
12
22
32
42
52
62
72
SUMP
BARIUM (mg/100g) CAPE FLEETWOOD L - 21
P + 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
12
22
12
22
32
42
52
62
72
82
SUMP
BARIUM (mg/100g) CAPE FLEETWOOD L - 21
15 - 20cm
0
20
40
60
80
85
65
45
25
5
22
12
22
32
42
52
62
72
SUMP
☐ 0.2 - 0.4
▧ 0.4 - 0.6
░ 0.6 - 0.8
▨ 0.8 - 1.0
▒ 1.0 - 1.2
■ 1.2 - 1.8

Figure 7. Barium concentrations in soil at Cape Fleetwood L-21.

Contour intervals are in dm and P+5 cm
-- 5 cm above the froze-table.

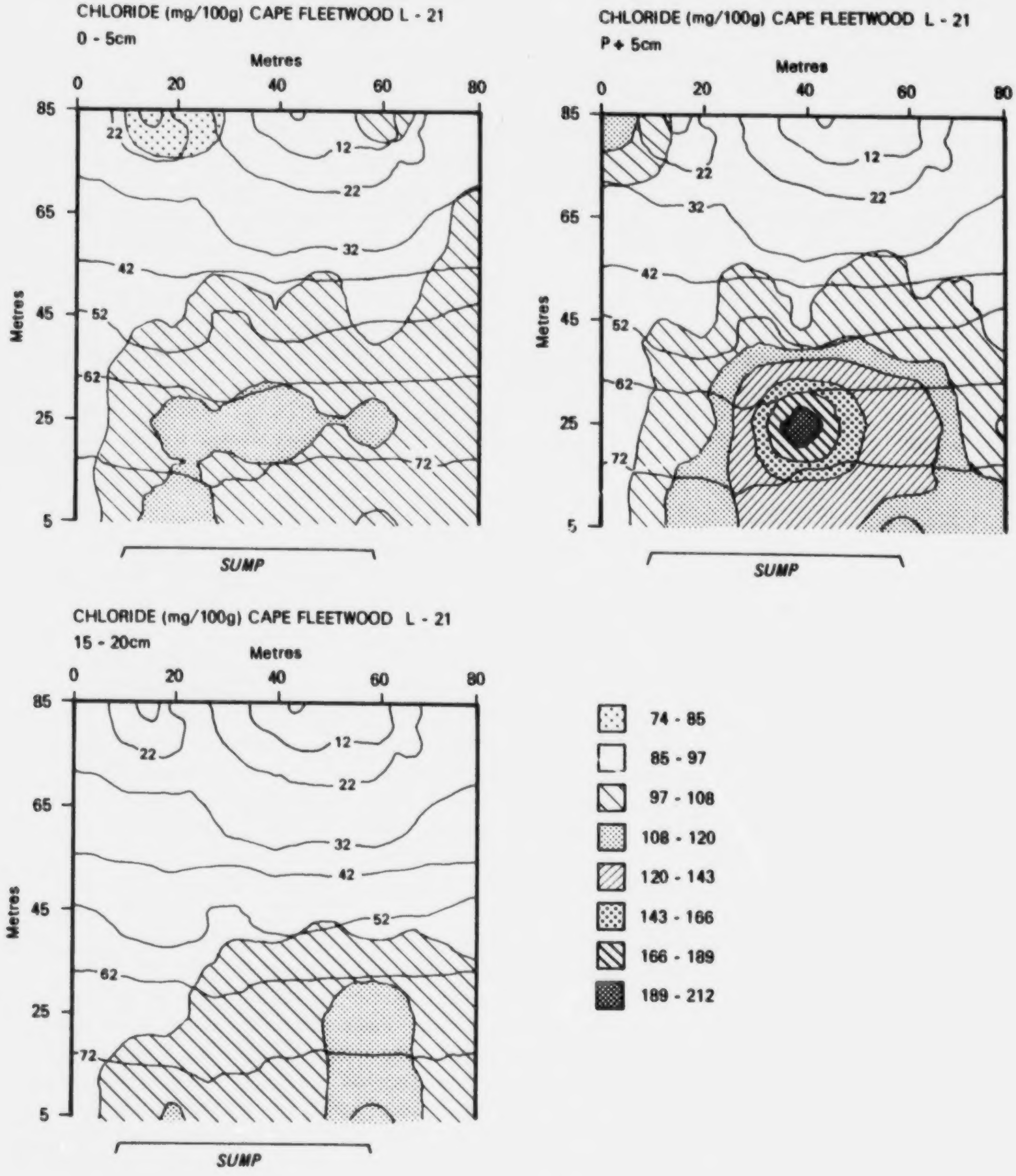

CHLORIDE (mg/100g) CAPE FLEETWOOD L - 21
0 - 5cm
CHLORIDE (mg/100g) CAPE FLEETWOOD L - 21
P + 5cm
CHLORIDE (mg/100g) CAPE FLEETWOOD L - 21
15 - 20cm
Metres
0
20
40
60
80
85
65
45
25
5
12
22
32
42
52
62
72
SUMP
74 - 85
85 - 97
97 - 108
108 - 120
120 - 143
143 - 166
166 - 189
189 - 212

Figure 8. Chloride concentrations in soil at Cape Fleetwood L-21.

Contour intervals are in dm and P+5 cm
-- 5 cm above the frost-table.

Although considerable amounts of barium carbonate were used in the mud system at Cape Fleetwood L-21 (Table 1), levels of extractable barium in soils downslope of the sump were very low (Table 2). Barium concentrations at 5 m from the sump were approximately 162% of background throughout the active layer but this difference was not significant. Mapping of soil barium distribution (Fig. 7) showed the highest concentrations at 15-20 cm depth within 5 m to 10 m of the sump. There was little evidence of barium movement downslope. Barium concentrations in gullies measured at 40 m from the sump (ca. 0.05 mg/100 g throughout the active layer) were slightly higher than background levels, but the differences were small.

Concentrations of acetate-extractable manganese in soil were very low (Table 2). There was no evidence of manganese contamination of soil close to the sump. In fact, manganese concentrations throughout the active layer were below background levels in the area immediately adjacent to the downslope berm. Higher soil manganese levels in less disturbed areas were probably a result of increases in organic content of the soil concomittent with increased plant cover.

Extractable levels of copper, zinc, lead and chromium in soil were insignificant, ranging from 0.04-0.002 mg/100 g. Downslope concentrations of these cations were little different from background levels and did not vary according to proximity to the sump.

Mean levels of extractable soil chloride are given in Table 2. Analysis of variance indicated a significant trend of diminishing chloride concentrations downslope of the sump at soil depths of 0-20 cm. This trend also occurred in the basal 5 cm of the active layer but was insigniificant due to lateral variation in chloride levels, especially at 25 cm from the sump (Table 2). Relatively high levels of chloride were present throughout the active layer at distances of 5-25 m from the sump. Chloride concentrations averaged 120% of background levels in this area (Table 2).

Migration of highly mobile chloride downslope was evident at Cape Fleetwood L-21. Concentrations at the surface and base of the active layer were greater at 25 m from the sump than at 5 m (Fig. 8). An extremely high concentration of chloride immediately above the frost-table was measured at one point 25 m from the sump (Fig. 9). Reasons for this are not known. No marked depression of the frost-table with consequent ponding of ion-rich soil water was evident at this point (see Figure 4, line 3). Presumably, the high concentration must have resulted from some peculiarity in soil characteristics or sub-surface drainage.

Table 3. Mean soil pH (with standard errors) at Cape Fleetwood L-21

Soil depth (cm)	pH at distance from sump (m) 5	25	45	65	85	UD
0 - 5 *	7.7 ± 0.5	6.4 ± 0.1	6.7 ± 0.1	6.3 ± 0.4	6.9 ± 0.5	6.2 ± 0.1
15 - 20 *	7.3 ± 0.4	6.0 ± 0.1	6.4 ± 0.1	6.5 ± 0.2	6.9 ± 0.3	6.3 ± 0.05
P + 5 *	6.9 ± 0.4	6.4 ± 0.1	6.8 ± 0.2	6.9 ± 0.3	7.6 ± 0.1	6.5 ± 0.1

*anova significant at $P_{0.05}$ level UD - undisturbed area P - frost-table

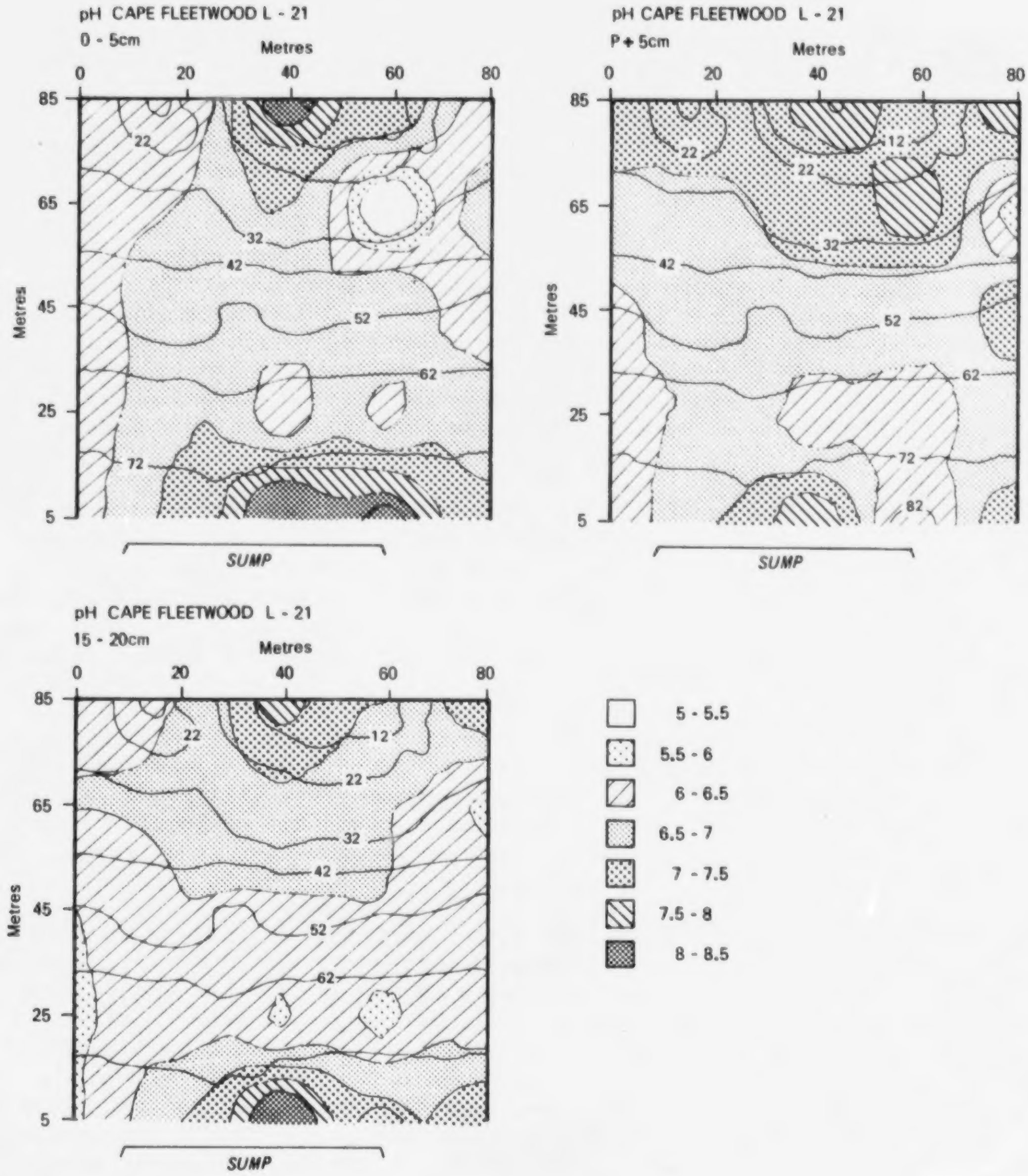

pH CAPE FLEETWOOD L - 21
0 - 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
22
32
42
52
62
72
SUMP
pH CAPE FLEETWOOD L - 21
P + 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
12
22
22
32
42
52
62
72
82
SUMP
pH CAPE FLEETWOOD L - 21
15 - 20cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
12
22
22
32
42
52
62
SUMP
5 - 5.5
5.5 - 6
6 - 6.5
6.5 - 7
7 - 7.5
7.5 - 8
8 - 8.5

Figure 9. Soil pH at Cape Fleetwood L-21.

Contour intervals are in dm and P+5 cm -- 5 cm above the frost-table.

Mean soil chloride concentrations (mg/100 g) measured in downslope gullies at approximately 40 m from the sump were 175.3 at 0-5 cm depth; 153.9 at 15-20 cm depth; and, 101.0 at 5 cm above the frost-table. These levels were considerably higher than in the surrounding soil indicating contamination of drainage systems by chloride-rich sump materials.

5.1.4 Soil pH:

Significant trends of variation in soil pH downslope of the sump were evident throughout the entire active layer (Table 3). Relatively high pH values within 10 m of the sump were undoubtably caused by the increase in soil ionic content associated with spillage of drilling fluids. Elevated soil pH levels, compared to background, at 85 m from the sump (Table 3) occurred at the confluence of two gullies. Soil pH values 40 m downslope from the sump in gullies (ranging from 7.8 at 0-5 cm depth to 6.8 at 15-20 cm depth) were also higher than background levels. These results add weight to the analysis that ion-rich sump materials were concentrated in natural drainageways. The pH distribution maps (Fig. 9) indicated that areas of slightly alkaline soils were quite restricted. Soils downslope of the sump were slightly acidic in the main and increases in pH over background at 25 m to 65 m were only marginal (Table 3).

5.1.5 Surface water ion content:

Concentrations of cadmium, chromium, zinc, copper, lead and manganese in flowing water were insignificant, ranging from 0-0.01 mg/l. Levels of highly soluble potassium, sodium and chloride were 8.1, 86.3 and 1,120.6 mg/l respectively. The water samples were collected in a downslope drainageway 80 m from the sump.

Measurement of background ion levels in flowing water sampled in undisturbed areas was not possible at Cape Fleetwood. Significant contamination of downslope watercourses was indicated, however, by comparison of the L-21 values with background levels in flowing water at Robert Harbour K-07 (Table 20). Sodium and chloride concentrations were approximately 1,086% and 1,748% of background respectively. Cape Fleetwood L-21 and Robert Harbour K-07 are roughly comparable in terms of soil, vegetation and microtopography.

5.1.6 Vegetation distribution:

Percentage frequencies of plant species recorded at Cape Fleetwood L-21 are listed in Table 4. Slightly fewer species occurred downslope compared to undisturbed areas. Reduction in species richness of the vegetation (26%) was greatest 5 m from the berm.

Table 4. Percentage frequency of plant species at Cape Fleetwood L-21 (UD -- undisturbed vegetation)

Species	Distance from sump (m)					
	5	25	45	65	85	UD
MOSSES						
Ditrichum flexicaule	35	55	70	90	80	100
Pogonatum alpinum var. septentrionale	35	55	90	100	90	100
Dead moss	60	95	95	100	90	100
LICHENS						
Cetraria cucullata	25	80	80	75	65	100
Cetraria delisei	35	75	75	90	75	100
Cetraria tilesii		5				25
Parmelia omphalodes	25	60	60	75	65	75
Pertusaria dactylina	25	85	80	75	90	100
Pseudephebe pubescens			5		20	38
Thamnolia subuliformis	50	80	90	90	80	100
HIGHER PLANTS						
Alopecurus alpinus	30	100	65	75	40	100
Cardamine bellidifolia	25	55	60	90	75	100
Draba alpina						25
Draba corymbosa	25	60	85	85	70	100
Luzula sp.	60	95	100	100	90	100
Minuartia rossii	10	30	30	5	40	88
Oxyria digyna		10			10	38
Papaver radicatum	30	75	95	80	70	100
Potentilla hyparctica			5			25
Ranunculus sulphureus		15	20	40	10	38
Saxifraga caespitosa	10	35	15	20	40	88
Saxifraga flagellaris ssp. platysepala						100
Saxifraga foliolosa	5	35	45	70	40	100
Saxifraga nivalis	20	70	80	70	65	88
Saxifraga oppositifolia	10	75	80	85	60	75
Saxifraga rivularis	15	65	65	95	80	100
Stellaria monantha	40	50	35	25	55	25
VDI	21	50	53	57	52	79

VDI - vegetation disturbance index (%)

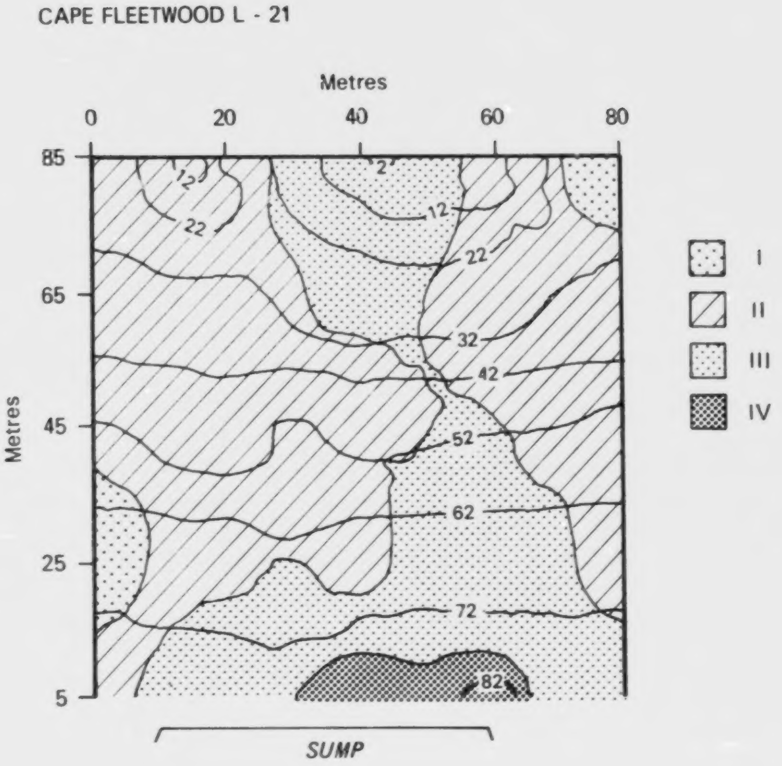

CAPE FLEETWOOD L - 21
Metres
0
20
40
60
80
85
65
45
25
5
Metres
12
22
2
12
22
32
42
52
62
72
82
I
II
III
IV
SUMP

Figure 10. Community disturbance (CD) class map of Cape Fleetwood L-21.

Contour intervals are in dm and vegetation ranges from least disturbed (Class I) to most disturbed (Class IV).

Occurrence of nearly all species was greatly reduced in disturbed areas within 10 m of the sump (Table 4). Species frequency generally increased with distance downslope, although, for many species, increases at 25-85 m from the berm were not large. Thamnolia subuliformis (Ehrh.) W. Culb., Luzula spp. and Stellaria monantha Hulten, occurred with relatively high frequencies close to the sump. Presumably, these species represent some of the more disturbance-resistant elements of the vegetation. No species increased in occurrence in disturbed areas.

VDI values, representing a composite measure of species frequency and richness, demonstrated effects of disturbance on the vegetation complex in summary form. Disruption was clearly greatest within 5 m of the berm, but VDI at 85 m distance was still 27% lower than the value for the undisturbed area (Table 4). Vegetation disturbance at 85 m and greater distances from the sump occurred in areas of extensive gully erosion. The sharp increase in VDI at 25 m downslope from the sump (Table 4) indicated that the worse effects of vegetation disruption were confined to a small area at Cape Fleetwood.

Axis 1 of the reciprocal averaging ordinations accounted for 35% of the variation in species incidence data. There was also some distribution of sample points on axis 2 (accounting for 18% of the residual variance). These two axes together accounted for 53% of the variability in species incidence.

CD class IV (the most disturbed vegetation) was confined to a small area immediately adjacent to the sump at Cape Fleetwood (Fig. 10). Levels of various soil ions were high in this area and overburden burial of the vegetation was virtually complete. Distribution of intermediately disturbed vegetation (CD class III) between 5 m and 45 m downslope (Fig. 10) coincided almost exactly with the extensive area of fill overburden sheet-washed from the sump. Partial burial of vegetation was noted in this area with some recolonization, mainly by Alopecurus alpinus. Class III distribution at 65-85 m associated with a well-developed gully. Vegetation disturbance in CD class II and I areas (Fig. 10) was minimal. Class I vegetation was virtually undisturbed.

5.1.7 Ion content of plants:

Concentrations of potassium, sodium, chromium, zinc and chloride in some of the dominant species at Cape Fleetwood L-21 are listed in Table 5.

Gradients of increasing salt content (sodium and chloride) were best defined in Alopecurus alpinus and Luzula spp. Chloride concentration in Alopecurus 25 m from the sump was 176% of that at 85 m downslope. Levels of chloride and sodium in Luzula spp.

Table 5. Concentrations (mg/100 g) of total potassium, sodium, chromium, zinc and chloride in plant species at Cape Fleetwood L-21 (UD -- undisturbed area)

Species	Distance from sump (m)				
	5	25	45	65	85	UD
POTASSIUM						
Alopecurus alpinus		45.9		42.5	82.4	
Ditrichum flexicaule		5.4	6.3	6.8	17.1	12.2
Luzula sp.	24.8	12.9	20.8		9.5	36.5
Oxyria digyna		40.6			24.3	72.3
Papaver radicatum		57.4	16.2		70.2	95.9
Saxifraga oppositifolia			11.5	20.3	28.4	20.3
SODIUM						
Alopecurus alpinus		200.0		71.3	47.5	
Ditrichum flexicaule		44.1	54.6	41.6	67.6	31.1
Luzula sp.	489.5	63.9	65.2		78.6	29.8
Oxyria digyna		315.3			74.4	151.3
Papaver radicatum		160.3	20.6		24.8	18.3
Saxifraga oppositifolia			51.8	39.0	22.6	18.1
CHROMIUM						
Alopecurus alpinus		59.0		0.8	21.3	
Ditrichum flexicaule		1.6	9.7	7.1	40.4	1.0
Luzula sp.	0.2	0.3	1.0		1.0	trace
Oxyria digyna		trace			0.5	1.0
Papaver radicatum		12.7	1.4		22.3	trace
Saxifraga oppositifolia			5.4	6.0	1.2	1.0
ZINC						
Alopecurus alpinus		7.5		7.7	7.3	
Ditrichum flexicaule		10.0	5.9	6.7	6.2	5.3
Luzula sp.	10.0	11.3	10.2		6.0	9.0
Oxyria digyna		7.5			7.0	6.3
Papaver radicatum		7.7	7.3		7.3	6.0
Saxifraga oppositifolia			9.3	6.8	6.1	4.8

Table 5. continued

CHLORIDE						
Alopecurus alpinus		5,798.2		3,819.0	3,289.3	
Ditrichum flexicaule		1,728.3	1,709.9	6,095.4	1,579.6	892.0
Luzula sp.	5,463.7	3,373.0	3,278.2		2,007.0	2,676.1
Oxyria digyna		2,982.7			2,397.3	2,007.0
Papaver radicatum		4,237.2	2,564.6		2,453.0	3,117.9
Saxifraga oppositifolia			2,146.5	8,028.3	2,034.9	2,118.6

adjacent to the sump berm were 204% and 1,643 % of background respectively. Other species, notably Oxyria digyna and Saxifraga oppositifolia, also concentrated salt in their tissues but gradients of accumulation with respect to distance from the sump were not well defined.

Very high salt contents of Ditrichum flexicaule and Saxifraga oppositifolia 65 m downslope possibly reflected growth in salt-rich soil at the base of a natural gully. Salt encrustations on stems and leaves of these mat-forming species may also have given erroneously high tissue concentration readings.

Chromium concentrations were relatively high in Alopecurus alpinus, Ditrichum flexicaule and Papaver radicatum. These results were surprising in that very little chromium was present in the soils at Cape Fleetwood. Presumably, the small amounts of chromium available to plants were quickly taken up and concentrated by these few species. Tissue concentrations of chromium were highest in plants growing in drilling fluid contaminated areas close to the sump and in a natural gully at 85 m downslope.

Tissue levels of potassium and zinc were low in all of the species sampled. Background potassium concentrations generally tended to be higher than those in plants growing downslope of the sump. Reasons for this phenomenon are not known.

5.2 Bent Horn N-72

5.2.1 Site description and well history:

Bent Horn N-72 (76° 21' 51.00"N 103° 58' 15.00"W) is located on low-lying, gently sloping and well vegetated tundra at the head of Bent Horn inlet on the southwest coast of Cameron Island (Fig. 1).

The Bent Horn area is a sloping sequence of shallow raised beach materials overlying consolidated sandstone bedrock (Trold Fiord Formation). French (1978a) reported the existence of a well developed network of ice wedges forming a polygonal net penetrating the frozen bedrock. A thick organic layer (5-15 cm) composed mainly of moss overlies the beach materials. The active layer is extremely shallow and the tops of ice wedges occur within 15 cm or less of the ground surface (French 1978a). Average slope gradients at Bent Horn are low, with slope angles less than 4° occurring widely. Natural gully development is constrained by the low relief. Drainage pattern is dendritic.

Bent Horn N-72 is a capped oil producing well drilled to a final depth of 4,384 m. The well was spudded in November 1973 and completed in April 1974. A variety of mud systems were used in the drilling operation (depths are in metres):

0 - 307	Salt gel - Kelzan X-C polymer system
307 - 1,324	Kelzan X-C polymer system
1,234 - 3,274	Fresh gel - Kelzan X-C polymer system
3,274 - 4,384	Fresh gel - Kelzan X-C polymer system

Total quantities of mud solids and liquid additives (excluding water) plus washing agents are reported in Table 6. Freshwater formed the bulk of the liquid component of the mud systems.

Drilling fluid wastes were discharged to a sump of dimensions ca 41 m x 41 m x 3 m excavated in imperfectly drained fine silt and clay with some coarse gravel intermixed. The sump was situated slighly upslope of the well (Fig. 11). Sump infill material consisted of stones up to 50 cm in diameter and finer gravel. There was no history of sump problems occurring during drilling or sump infilling. Observations made in 1976 (Beak Consultants, Calgary) indicated that some slumping of sump infill had occurred together with ponding of surface water. Drilling fluids, however, were still contained.

No sump problems were evident at Bent Horn N-72 when the site was visited in July 1977. There were salt encrustations on the sump infill but sheetwashing of this material downslope had not occurred.

Table 6. Total quantities of solids and liquids (excluding water) discharged to well sump at Bent Horn N-72

Product	Description	Quantity
	SOLIDS	KILOGRAMS
Barite	Barium sulphate	146,409
Bentonite	Montmorillonite clay	54,500
	Salt gel	3,364
Kelzan X-C polymer	Xanthan gum	12,068
Caustic soda	Sodium hydroxide	2,929
	Sawdust	3,000
Kwik-seal	Wood fiber and cellophane	6,100
	Mica	1,523
	Walnut shells	455
Celloflakes		341
Dowicide B	Sodium trichlorophenate	93
	Sodium chromate	1,068
	Sodium bicarbonate	864
C.M.C.	Sodium carboxymethyl cellulose	45
Fibre seal		182
	Gypsum	623
	Chrome alum	2,830
Supercol		1,659
TOTAL		238,053
	LIQUIDS	LITRES
Detergent Milchem M-D		182
TOTAL		182

Plate 2.

Subsidence of gravel sump fill at Bent Horn N-72.

Ridges of organic matter and dead plants thrown up by heavy vehicle movement at Bent Horn N-72.

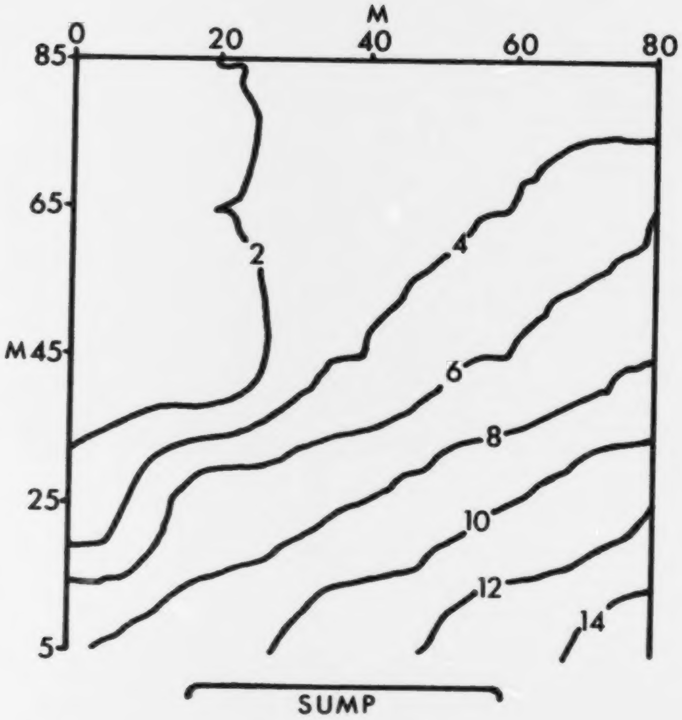

M
0
20
40
60
80
85
65
M45
25
5
2
4
6
8
10
12
14
SUMP

Figure 11. Topography at Bent Horn N-72
(contour intervals in dm).

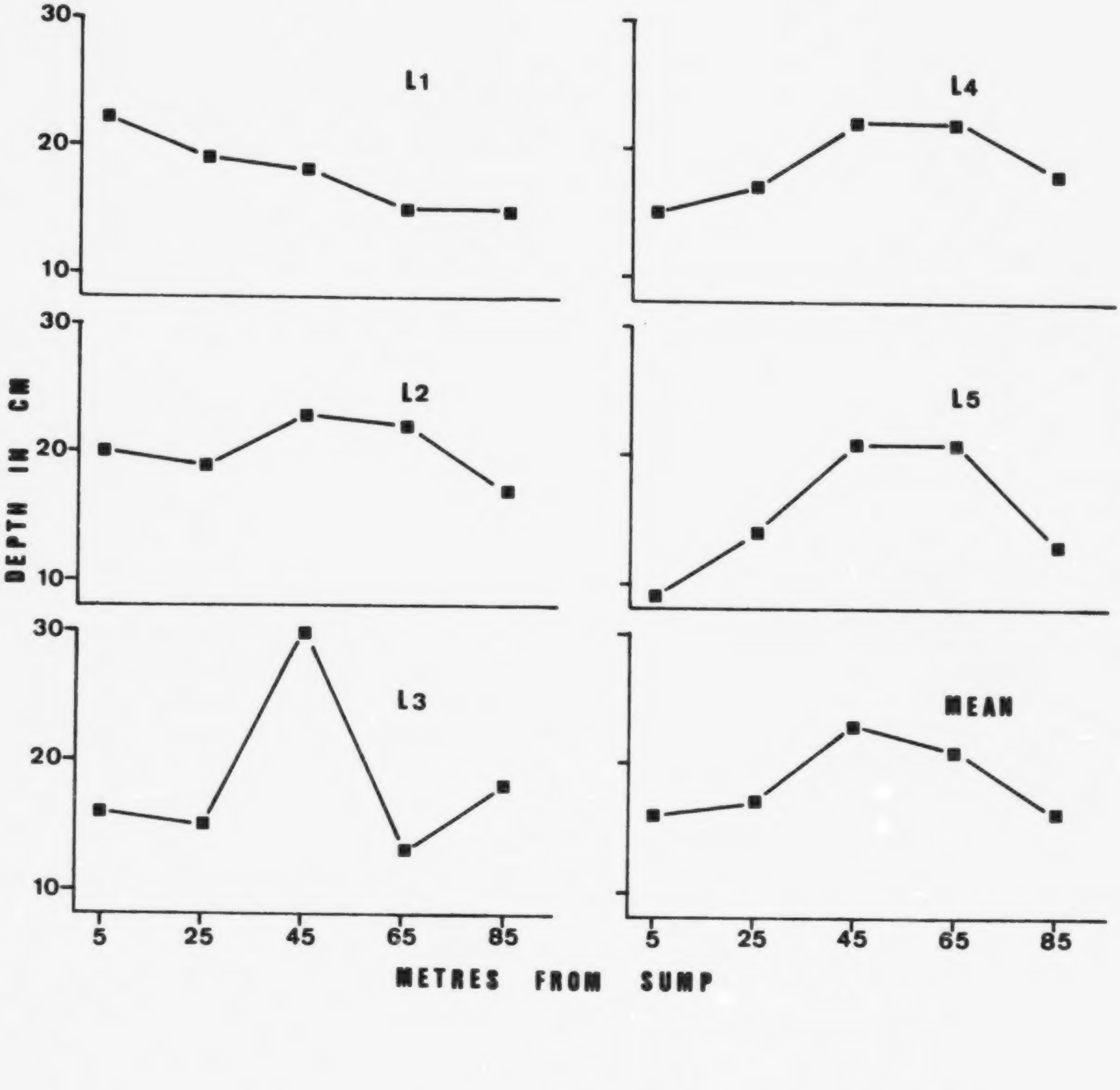


Figure 12. Active layer depth at Bent Horn N-72 (measured on July 17, 1977).

Vegetation disturbance appeared to be largely a function of scarification. The organic mat and plant cover at 5-45 m downslope from the sump was severely disrupted by scraping and rutting resulting from heavy vehicle movement. Use of vehicles at times when the active layer had thawed was indicated by the severity of rutting (Plate 2). Vehicle tracks were much in evidence at 45 m to 65 m from the sump. In places this vehicle passage had thrown up ridges of organic matter and dead moss. Plant cover was incomplete between these ridges, the soil was severely compacted, and water had ponded on the soil surface. The only undisturbed vegetation in the sample grid was at 85 m from the sump in a waterlogged low-lying area adjacent to a natural pond. Plant cover in this area, mainly mosses, was 100 percent.

5.2.2 Active layer depth:

The existence of a thick organic mat overlying the soil at Bent Horn N-72 provides excellent insulation to the underlying permafrost and contributes to the thin active layer noted in July at this site. The mean depth of thaw exceeded 20 cm at a few points downslope of the sump (Fig. 12), but active layer depth across the sample grid generally averaged 14-17 cm.

The sharp increase in active layer depth at 45 m from the sump on line 3 (Fig. 12) did not appear to be associated with any surface features. However, surface scarification by vehicle movement was extensive and probably resulted in increased thaw rates in some places. Removal of insulating vegetation by tracked vehicle passage and consequent soil warming due to surface albedo changes would account for increases in active layer depth.

5.2.3 Soil ion content:

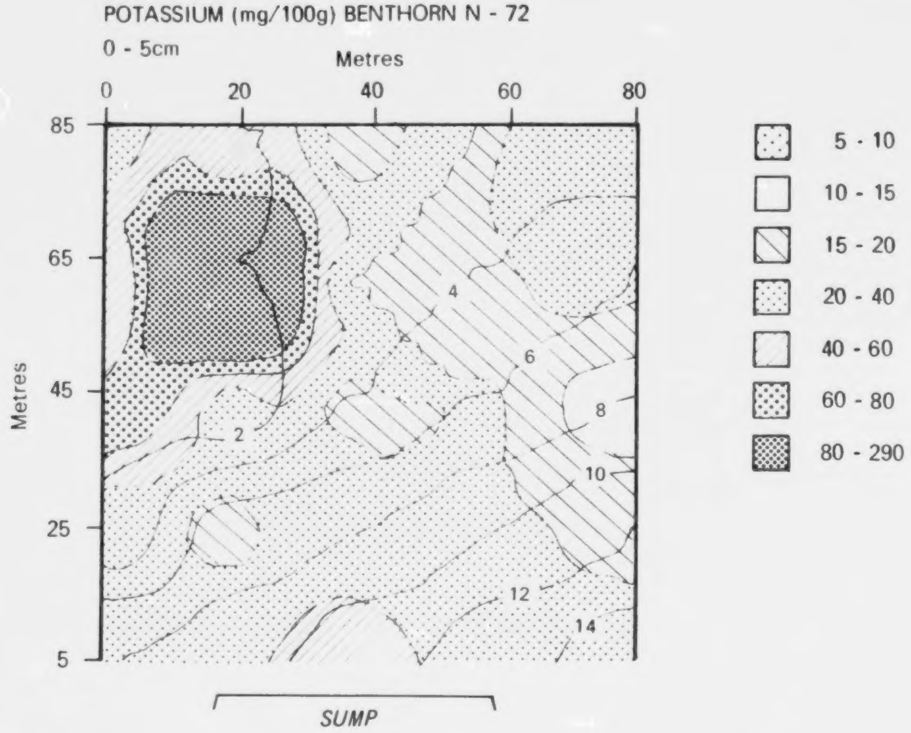
Mean levels of ammonium acetate-extractable potassium in soil at Bent Horn N-72 did not differ significantly from background levels (Table 7). Potassium at this site was concentrated at the soil surface where levels were almost three times higher than at the base of the active layer. There was inconclusive evidence of elevated potassium concentrations in surface soil at 5 m and 10 m downslope of the sump (Fig. 13). The accumulation of this cation at 65 m from the sump (Table 7) was due to greatly elevated levels at one point (Fig. 13). This sampling point was located in a wet area which suggests that concentration of highly mobile potassium occurred in ponded surface waters.

Mean concentrations of acetate-extractable sodium were appreciably higher than background levels at all soil depths throughout the sample grid (Table 7). Widespread downslope movement of sodium-

Table 7. Mean concentrations (with standard errors) of extractable cations and chloride in soil at Bent Horn N-72

Soil depth (cm)	Concentration (mg/100 g) at distance from sump (m) 5	25	45	65	85	UD
POTASSIUM						
0 - 5	32.2 ± 6.9	20.2 ± 4.3	27.9 ± 11.8	76.1 ± 55.6	27.6 ± 6.3	28.4 ± 12.5
P + 5	15.3 ± 1.3	12.6 ± 1.3	14.9 ± 0.6	12.5 ± 0.7	12.0 ± 1.3	10.3 ± 0.8
SODIUM						
0 - 5	86.1 ± 23.5	46.7 ± 15.5	56.4 ± 29.2	93.3 ± 67.8	22.9 ± 11.8	3.8 ± 0.8
P + 5 *	34.5 ± 7.1	22.2 ± 10.9	6.0 ± 1.2	6.3 ± 1.7	9.9 ± 6.8	2.8 ± 0.3
BARIUM						
0 - 5	1.9 ± 0.4	1.4 ± 0.2	1.5 ± 0.2	1.3 ± 0.2	1.6 ± 0.1	1.3 ± 0.1
P + 5	1.4 ± 0.3	2.0 ± 0.2	2.0 ± 0.1	1.9 ± 0.1	1.9 ± 0.1	1.5 ± 0.2
MANGANESE						
0 - 5	3.4 ± 1.2	5.1 ± 2.0	4.9 ± 0.1	4.9 ± 0.1	5.0 ± 0.1	1.7 ± 0.1
P + 5	3.9 ± 1.3	3.0 ± 1.2	8.9 ± 5.4	13.9 ± 6.4	7.1 ± 2.3	2.1 ± 0.9
ZINC						
0 - 5 *	0.05 ± 0.004	0.07 ± 0.02	0.09 ± 0.03	0.13 ± 0.03	0.20 ± 0.05	0.06 ± 0.005
P + 5	0.10 ± 0.03	0.09 ± 0.01	0.11 ± 0.03	0.14 ± 0.07	0.20 ± 0.03	0.20 ± 0.09
CHLORIDE						
0 - 5	151 ± 12	170 ± 16	181 ± 1	140 ± 21	146 ± 28	106 ± 6
P + 5 *	162 ± 22	128 ± 17	101 ± 1	103 ± 3	108 ± 10	100 ± 1

*anova significant at $P_{0.05}$ level UD - undisturbed area P - frost-table


POTASSIUM (mg/100g) BENTHORN N - 72
0 - 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
2
4
6
8
10
12
14
SUMP
5 - 10
10 - 15
15 - 20
20 - 40
40 - 60
60 - 80
80 - 290

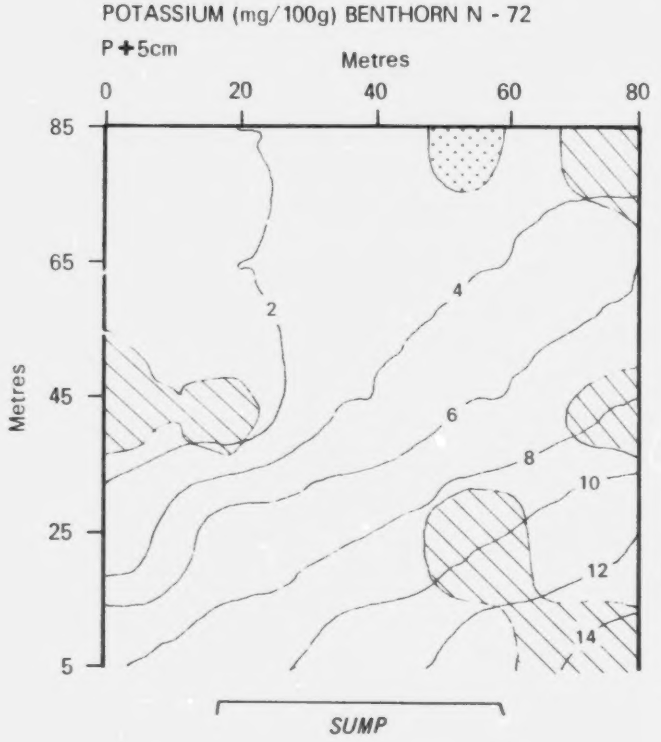

POTASSIUM (mg/100g) BENTHORN N - 72
P+5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
2
4
6
8
10
12
14
SUMP

Figure 13. Potassium concentrations in soil at Bent Horn N-72.

Contour intervals are in dm and P+5 cm -- 5 cm above the frost table.

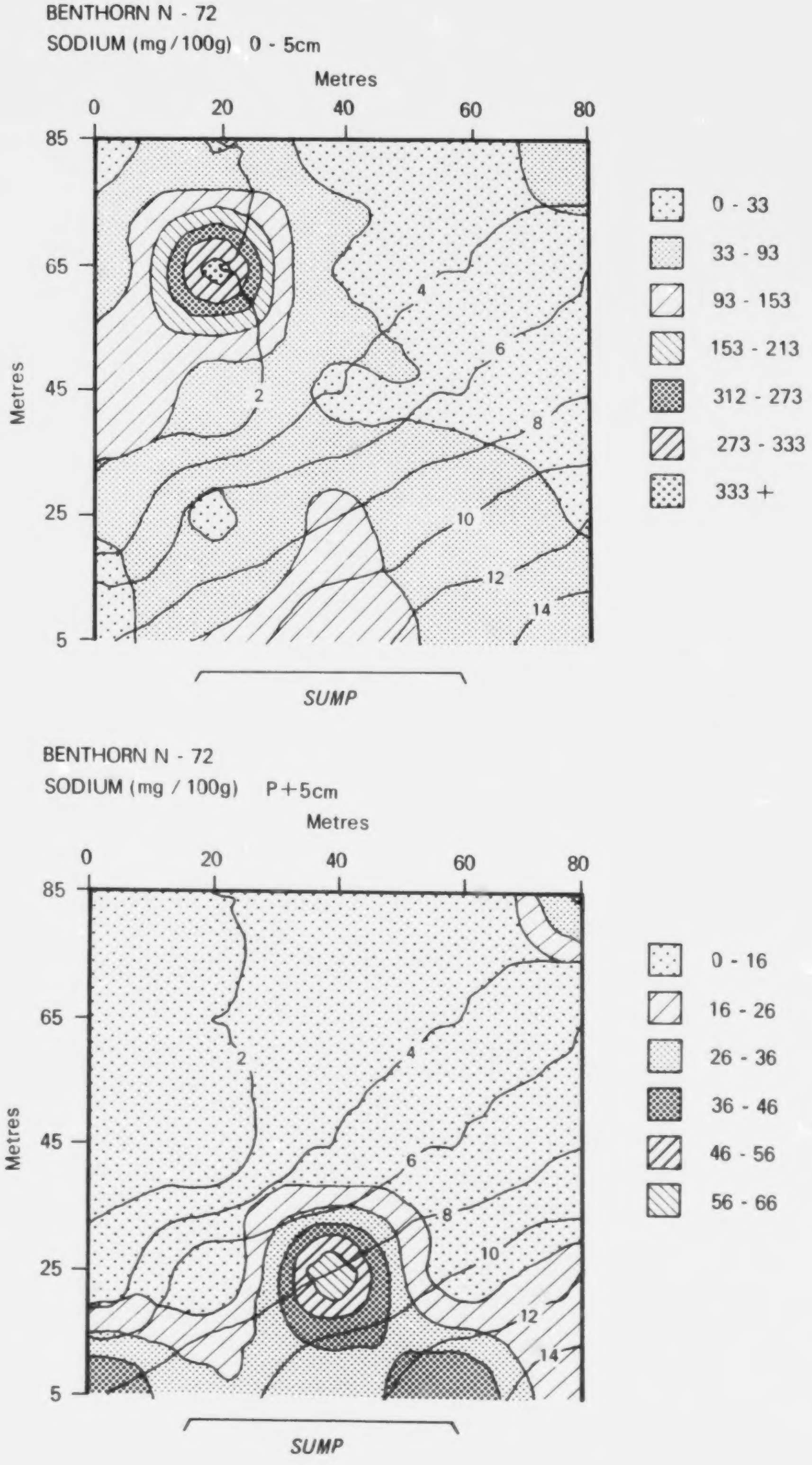

BENTHORN N - 72
SODIUM (mg/100g) 0 - 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
2
4
6
8
10
12
14
SUMP
0 - 33
33 - 93
93 - 153
153 - 213
312 - 273
273 - 333
333 +
BENTHORN N - 72
SODIUM (mg / 100g) P+5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
2
4
6
8
10
12
14
SUMP
0 - 16
16 - 26
26 - 36
36 - 46
46 - 56
56 - 66

Figure 14. Sodium concentrations in soil at Bent Horn N-72.

Contour intervals are in dm and P+5 cm -- 5 cm above the frost-table.

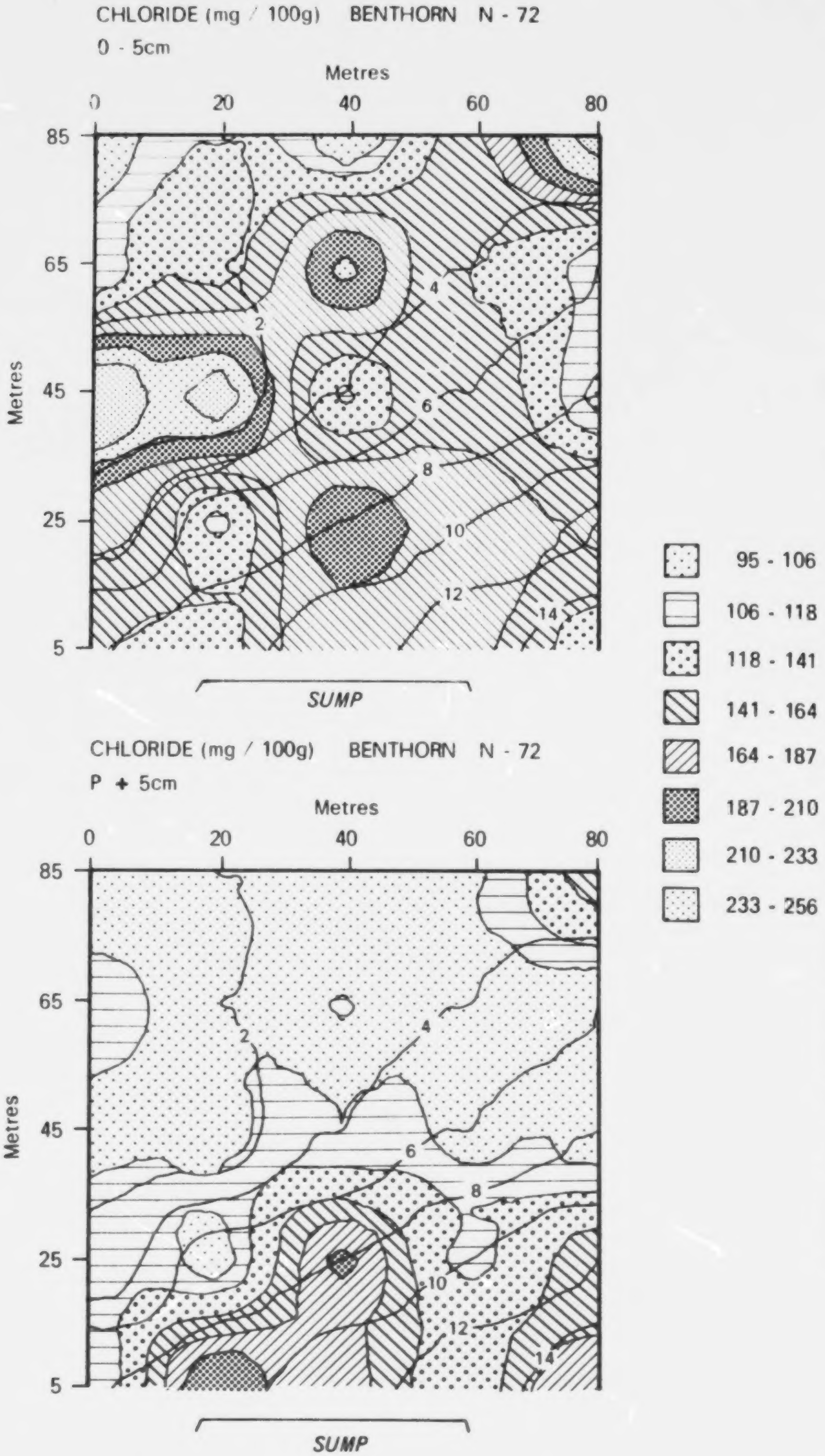

CHLORIDE (mg / 100g) BENTHORN N - 72
0 - 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
2
4
6
8
10
12
14
SUMP
CHLORIDE (mg / 100g) BENTHORN N - 72
P + 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
2
4
6
8
10
12
14
SUMP
95 - 106
106 - 118
118 - 141
141 - 164
164 - 187
187 - 210
210 - 233
233 - 256

Figure 15. Chloride concentrations in soil at Bent Horn N-72.

Contour intervals are in dm and P+5 cm
-- 5 cm above the frost-table.

rich sump materials had obviously occurred. Sodium levels at 0-5 cm depth between 5 m and 25 m from the sump were 1,747% of background on average. Corresponding concentrations at the base of the active layer were 1,013% of background. Sodium concentrations at the soil surface 85 m from the sump were 603% of background. The very high concentration of this ion at 65 m from the sump (Table 7) was 2,455% of background and represented accumulation measured at one sample point (Fig. 14). This point was located in the area of maximum potassium accumulation. Presumably, the reasons for concentration of these two ions downslope were the same.

A large amount of barium sulphate was used in the drilling mud system at Bent Horn N-72 (Table 7), but this was not reflected by elevated levels of extractable barium in the soil. Barium concentrations downslope of the sump were not significantly different from background levels (Table 7) and no barium seepage from the sump was evident.

Concentrations of extractable manganese in the organic soil at Bent Horn N-72 were relatively high compared, for example, to levels measured in the sands at Cape Fleetwood L-21. However, there appeared to be no correlation between soil manganese concentration and distance from the sump (Table 7). Levels, generally, were slightly higher than background throughout the sample grid. A high manganese concentration 65 m from the sump immediately above the frost-table (Table 7) was measured at one sample point. Water-logging of the soil and its retardation of organic matter breakdown at this location may have influenced manganese accumulation to some extent.

Downslope concentrations of extractable copper, lead, chromium and cadmium were very low, ranging from 0-0.03 mg/100 g, and were not correlated with distance from the sump.

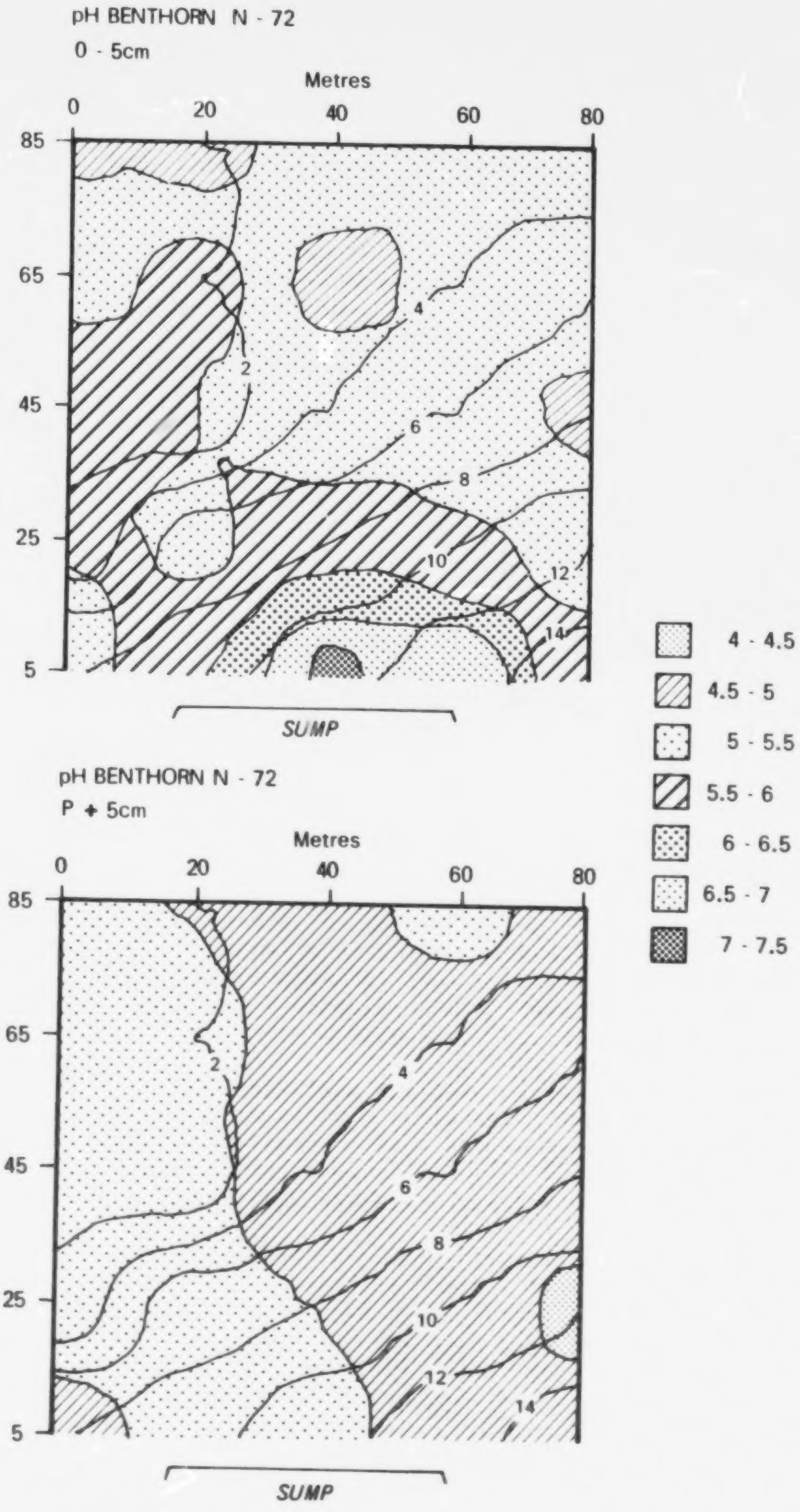
Extractable zinc in soils tended to increase with increasing distance from the sump (Table 7). This trend was significant at 0-5 cm soil depth. Zinc levels were generally low (maximum 0.20 mg/100 g) throughout the sample grid. The very low concentrations close to the sump are difficult to explain in terms of the effects of drilling activities. However, it is possible that mixing of mineral soil with the natural organic horizons during sump construction and infilling altered soil conditions enough to tie up some of the exchangeable zinc in unavailable form.

Mean levels of extractable soil chloride at 0-5 cm (Table 7) show high concentrations of this ion occurring at all points in the sample grid downslope from the sump. Mean concentrations between 5 m and 45 m from the sump were 158% of background levels. At 85 m from the sump mean chloride levels at the soil surface

Table 8. Mean soil pH (with standard errors) at Bent Horn N-72

Soil depth	pH at distance from sump (m)					
(cm)	5	25	45	65	85	UD
0 - 5 *	6.3 ± 0.4	5.5 ± 0.2	5.3 ± 0.2	5.2 ± 0.2	5.0 ± 0.07	5.3 ± 0.2
P + 5	4.9 ± 0.1	4.9 ± 0.1	4.9 ± 0.1	4.9 ± 0.09	5.0 ± 0.07	5.2 ± 0.4

*anova significant at $P_{0.05}$ level   UD - undisturbed area   P - frost-table



pH BENTHORN N - 72
0 - 5cm

pH BENTHORN N - 72
P + 5cm

Metres
0
20
40
60
80
85
65
45
25
5
2
4
6
8
10
12
14
SUMP
4 - 4.5
4.5 - 5
5 - 5.5
5.5 - 6
6 - 6.5
6.5 - 7
7 - 7.5

Figure 16. Soil pH at Bent Horn N-72.

Contour intervals are in dm and P+5 cm
-- 5 cm above the frost-table.

were 138% of background. Although not statistically significant, this trend indicated that appreciable soil contamination by chloride-rich drilling fluids had occurred at Bent Horn N-72 (Fig. 15).

High chloride levels in the basal 5 cm of the active layer were more restricted in extent (Fig. 15). Contamination was evident at distances of 5 m to 25 m from the sump (Table 7), but chloride levels were only a little above background over the remainder of the sample grid. This trend was highly significant. Concentrations of soil chloride immediately above the frost-table. at 5 m to 25 m from the sump were about 146% of background (Table 7).

5.2.4 Soil pH:

Soils at Bent Horn N-72 were acidic, especially in the basal 5 cm of the active layer (Table 8). This was related to the very high amounts of organic material in the soil coupled with acid release resulting from anaerobic decomposition in waterlogged conditions. Significantly high soil pH values at 0-5 cm depth within 5 m from the sump (Fig. 16) were probably related to ion enrichment from spilled drilling fluids. Surprisingly, soil pH immediately above the permafrost did not show this trend. Soils at this depth were, perhaps, better buffered than at the surface. Soil pH was close to background throughout the active layer at most points downslope of the sump (Table 8).

5.2.5 Surface water ion content:

Water samples at Bent Horn N-72 were collected from pools of standing water located on the sump fill at 1 m from the berm and at distances of 30 m and 90 m downslope from the sump. Levels of water soluble potassium, sodium and chloride decreased dramatically away from the sump (Table 9).

Table 9 Ion content of standing water at Bent Horn N-72

Distance from the sump (m)	Ion concentration (mg/l)		
	K	Na	Cl
1	48.9	536.7	3,880.4
30	16.5	160.0	1,772.9
90	4.3	10.2	167.3

Standing water on the sump infill was heavily contaminated by drilling fluid wastes. Concentrations of potassium, sodium and chloride in pools 1 m from the sump were 1,037% and 5.162% and 2,220% greater than the levels measured 90 m downslope. Levels of cadmium, chromium, zinc, copper, lead and manganese were insignificant, ranging from 0-0.05 mg/l.

5.2.6 Vegetation distribution:

Species richness of vegetation 5 m from the sump at Bent Horn N-72 was 38% less than in undisturbed areas (Table 10). Reductions in species richness were also evident at all other downslope distances but these were less marked.

Frequency of all species was markedly reduced in the area of severe mechanical disturbance close to the sump (Table 10). Species occurrence generally increased downslope. The more disturbance-resistant species included *Ditrichum flexicaule*, *Pogonatum alpinum* var. *septentriowale* (Bird.) Bird. *Cetraria delisei* (Bury ex Schaer.) Th. Fr. and *Alopecurus alpinus*. These occurred with relatively high frequencies (compared to the undisturbed area) in the highly distrubed areas at 25 m from the sump. Even these species, however, were appreciably less frequent at 5 m from the berm (Table 10).

VDI values were low downslope of the sump compared to the value for the undisturbed area (Table 10) indicating widespread disturbance of vegetation. Disruption was greatest within 5 m of the sump berm where scarification was most extensive. The low VDI value at 85 m from the sump (30% lower than VDI for the undisturbed area) was related more to reduced species richness than low frequency of species occurrence (Table 10). No mechanical disruption of vegetation was evident at this distance from the sump. Reduction in species richness was a function of soil saturation by groundwater.

Axis 1 in the reciprocal average ordination accounted for 24% of the variation in species incidence. Axis 2 accounted for 17% of the residual variance. Only 41% of the total variation in species incidence was accounted for by these two axes indicating appreciable heterogeneity in the vegetation at Bent Horn N-72.

The highly disturbed CD class IV vegetation was confined to a small area within 10 m of the sump at Bent Horn (Fig. 17). Concentrations of some soil ions, principally chloride at the surface and subsurface sodium, were high in this area. Disruption of vegetation due to burial by overburden gravel and scarification

Table 10. Percentage frequency of plant species at Bent Horn N-72
(UD -- undisturbed vegetation)

Species	Distance from sump (m)					
	5	25	45	65	85	UD
MOSSES						
Aulacomnium turgidum	5	40	60	100	90	100
Ditrichum flexicaule	35	95	100	100	100	100
Plagiomnium medium ssp. curvatulum		20	40	85	55	100
Pogonatum alpinum var. septentrionale	25	75	100	80	100	100
Rhizomium sp.		30	40	75	45	50
Sphagnum sp.				20		
Dead moss	55	100	100	100	100	100
LICHENS						
Cetraria cucullata	15		10	15	20	88
Cetraria delisei	30	65	65	100	65	100
Parmelia omphalodes	20	50	70	100	60	100
Peltigera cfr. leucophlebia				10		
Pertusaria dactylina	40	45	95	80	75	100
Pseudephebe pubescens						63
Thamnolia subuliformis	35	50	100	70	70	100
Lichen sp.						25
HIGHER PLANTS						
Alopecurus alpinus	40	80	80	100	100	100
Cardamine bellidifolia	5			10	5	75
Draba corymbosa	5	40	10		10	88
Luzula sp.	25	40	60	30	45	100
Papaver radicatum			5			13
Ranunculus sulphureus		5	5	5		
Saxifraga foliolosa		5				38
Saxifraga nivalis	5	10				38
Saxifraga rivularis	10	40	60	60	35	100
Stellaria monantha	10	35	30	35	25	75
VDI	14	33	41	47	40	70

VDI - vegetation disturbance index (%)

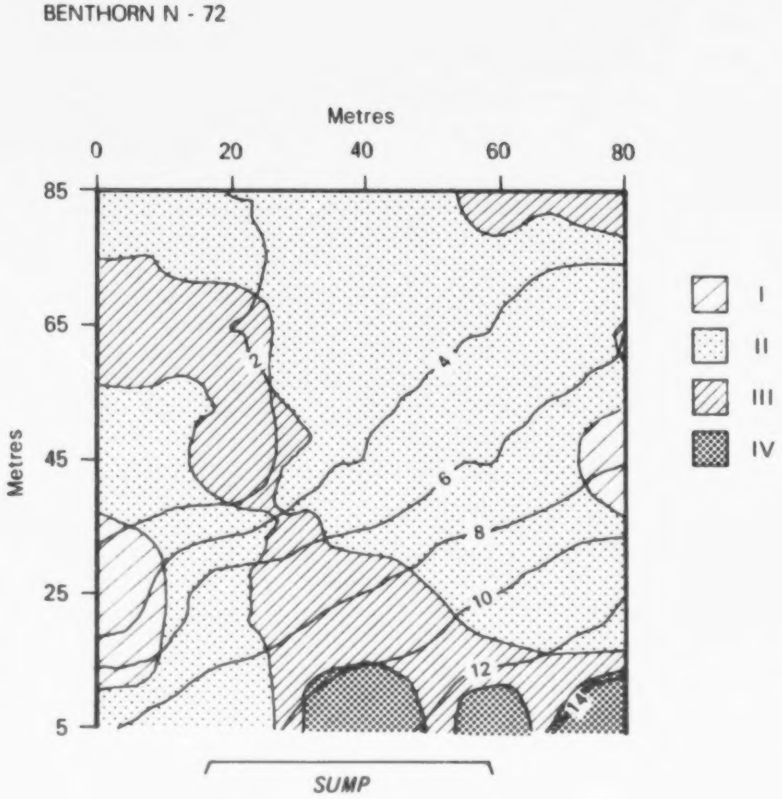

BENTHORN N - 72
Metres
0
20
40
60
80
85
65
45
25
5
Metres
2
4
6
8
10
12
14
I
II
III
IV
SUMP

Figure 17. Community disturbance (CD) class map of Bent Horn N-72.

Contour intervals are in dm and vegetation ranges from least disturbed (Class I) to most disturbed (Class IV).

Table 11. Concentrations (mg/100 g) of total potassium, sodium, zinc and chloride in plant species at Bent Horn N-72 (UD -- undisturbed area)

Species	Distance from sump (m)					
	5	25	45	65	85	UD
POTASSIUM						
Alopecurus alpinus	40.5	48.6	57.6	62.6	60.8	37.2
Aulacomnium turgidum				5.4	12.8	trace
Ditrichum flexicaule	10.8	11.7	9.45	10.8	10.8	1.4
SODIUM						
Alopecurus alpinus	390.0	690.8	389.8	305.7	176.1	44.6
Aulacomnium turgidum				90.1	90.1	21.3
Ditrichum flexicaule	95.0	248.0	317.4	155.1	51.0	21.0
ZINC						
Alopecurus alpinus	11.5	9.2	10.0	11.1	10.8	13.3
Aulacomnium turgidum				12.0	8.9	6.3
Ditrichum flexicaule	8.0	12.0	9.8	10.7		
CHLORIDE						
Alopecurus alpinus	4,878.3	5,798.2	6,541.6	5,374.5	3,846.9	2,899.1
Aulacomnium turgidum				1,728.3	2,752.8	1,616.8
Ditrichum flexicaule	1,477.4	2,685.4	2,174.3	2,100.0	1,728.3	1,240.5

was also common. Intermediately disturbed CD class III vegetation occurred in the heavily scarified area between 10 m and 30 m from the sump (Fig. 17). Distribution of class III vegetation 45-70 m downslope coincided with high levels of soil sodium, manganese and chloride. The small area of CD class III at 80-85 m from the sump (Fig. 17) was not indicative of disturbance but reflected species impoverishment in a transition zone between terrestrial and aquatic vegetation. Class II vegetation was widely distributed (Fig. 17) at N-72. Minimally disturbed CD class I vegetation was rare in comparison.

5.2.7 Ion content of plants:

Potassium, sodium and chloride concentrations in *Alopecurus alpinus* downslope of the sump were appreciably higher than background at Bent Horn N-72. Mean sodium and chloride levels in this species throughout the sample grid were 876% and 182% of background respectively (Table 11). Salt concentrations generally tended to be highest in plants growing in drilling fluid contaminated soils at 5-45 m from the sump.

Ditrichum flexicaule concentrated sodium in its tissues in contaminated areas, especially between 25 m and 65 m from the sump where levels were 1,144% of background on average (Table 11). Chloride levels in this species, however, were not high. Salt concentrations in *Aulacomnium turgidum* showed a similar trend at 65-85 m downslope. This species did not occur in amounts adequate enough for sampling between 5 m and 65 m from the sump.

Tissue concentrations of zinc were relatively low in all three dominants sampled at Bent Horn (Table 11). Zinc levels across the sample grid were similar to background and there was no correlation with distance of plants from contaminated areas close to the sump.

5.3 Charles Point G-07

5.3.1 Site description and well history:

Charles Point G-07 (76° 26' 26.75"N 103° 07' 0.306"W) is located on semi-polar desert terrain (with isolated patches of tundra meadow) on the southeast coast of Cameron Island (Fig. 1a). Regionally the landform is a coastal plain. The well is situated on an exposed beach ridge approximately one kilometre from the shoreline. Surface soils are silty sands covered in places by a desert 'armour' on fine stones.

Final drilling depth at G-07 was 3,865 m. The well was spudded on October 10, 1976 and completed on January 31, 1977. Amounts of solids used in drilling and discharged to the sump are reported in Table 12 together with total quantities of washing agents and liquid mud components (excluding water).

Waste drilling fluids were discharged to a sump approximately 40 m x 46 m x 4 m excavated in a shallow layer of silty sand overlying pure sand. The sump was located in an upslope position (Fig. 18). Slope angles of 2°-4° occurred adjacent to the sump berm on the ocean-facing side of the beach ridge. Sump infill material was coarse gravel, sand, and crushed rock. There was no history of sump problems during drilling or sump infilling operations.

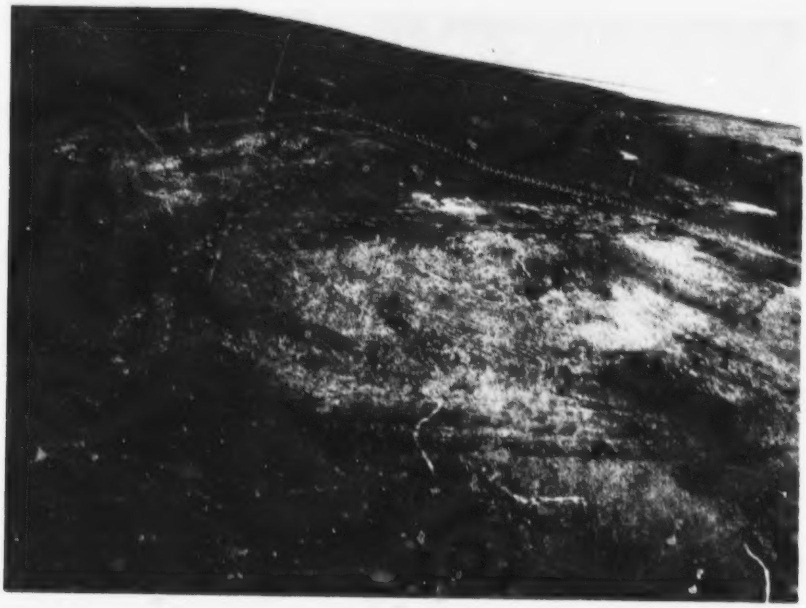
Some slumping of the sump infill with ponding of surface water was evident when the site was visited in 1977. Extensive salt accumulations were also noted on stones and soil immediately adjacent to the sump berm. Some drilling mud mixed with soil was present along the downslope berm but drilling fluids appeared to be contained. There was some evidence of downslope movement of sand overburden eroded from the sump but burial of the vegetation was minimal. Eroded materials were largely confined to a natural gully crossing the sample grid.

Visual assessment suggested that physical disturbance was slight at Charles Point G-07 and restricted largely to areas immediately adjacent to the sump (Plate 3). There was some disturbance in the NE corner of the grid (65-85 m from the sump) due to seismic drilling but the area affected was small. Relatively undisturbed vegetation occurred at 45 m to 85 m from the sump. Plant cover in the drier portions of this area was approximately 10% to 20%, and up to 90% (mainly mosses) in the wetter portions.

5.3.2 Active layer depth:

There was some evidence of increased permafrost thawing in mid-July at 5 m and 25 m from the sump(Fig. 19). This probably resulted from vehicle

Plate 3.



Air view of Charles Point G-07 showing sump fill and heavily scarified area close to the downslope sump berm.

Coarse gravel fill at Charles Point G-07 along edge of sump berm.

Table 12. Total quantities of solids and liquids (excluding water) discharged to well sump at Charles Point G-07

Product	Description	Quantity
	SOLIDS	KILOGRAMS
Barite	Barium sulphate	73,182
Bentonite	Montmorillonite clay	13,182
Kelzan X-C polymer	Xanthan gum	13,023
Peltex	Ferro-chrome lignosulphonate	500
Caustic soda	Sodium hydroxide	9,943
	Walnut shells	3,645
	Paraformaldehyde	500
	Sodium chromate	500
	Sodium bicarbonate	773
S.A.P.P.	Sodium acid pyrophosphate	91
C.M.C.	Sodium carboxymethyl cellulose	91
	Chrome alum	2,964
TOTAL		118,394
	LIQUIDS	LITRES
Adafoam		205
Will-do		659
TOTAL		864

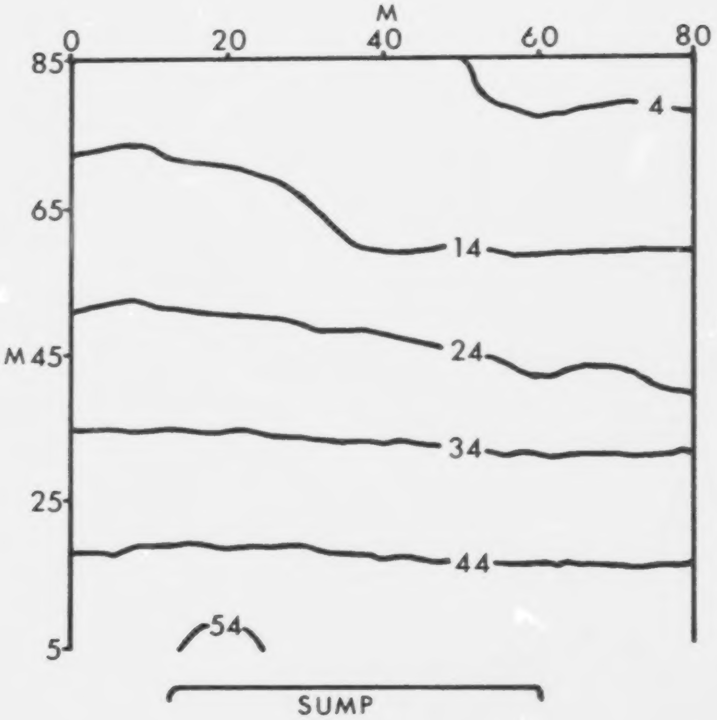

M
0
20
40
60
80
85
65
M 45
25
5
4
14
24
34
44
54
SUMP

Figure 18. Topography at Charles Point G-07 (contour intervals in dm).

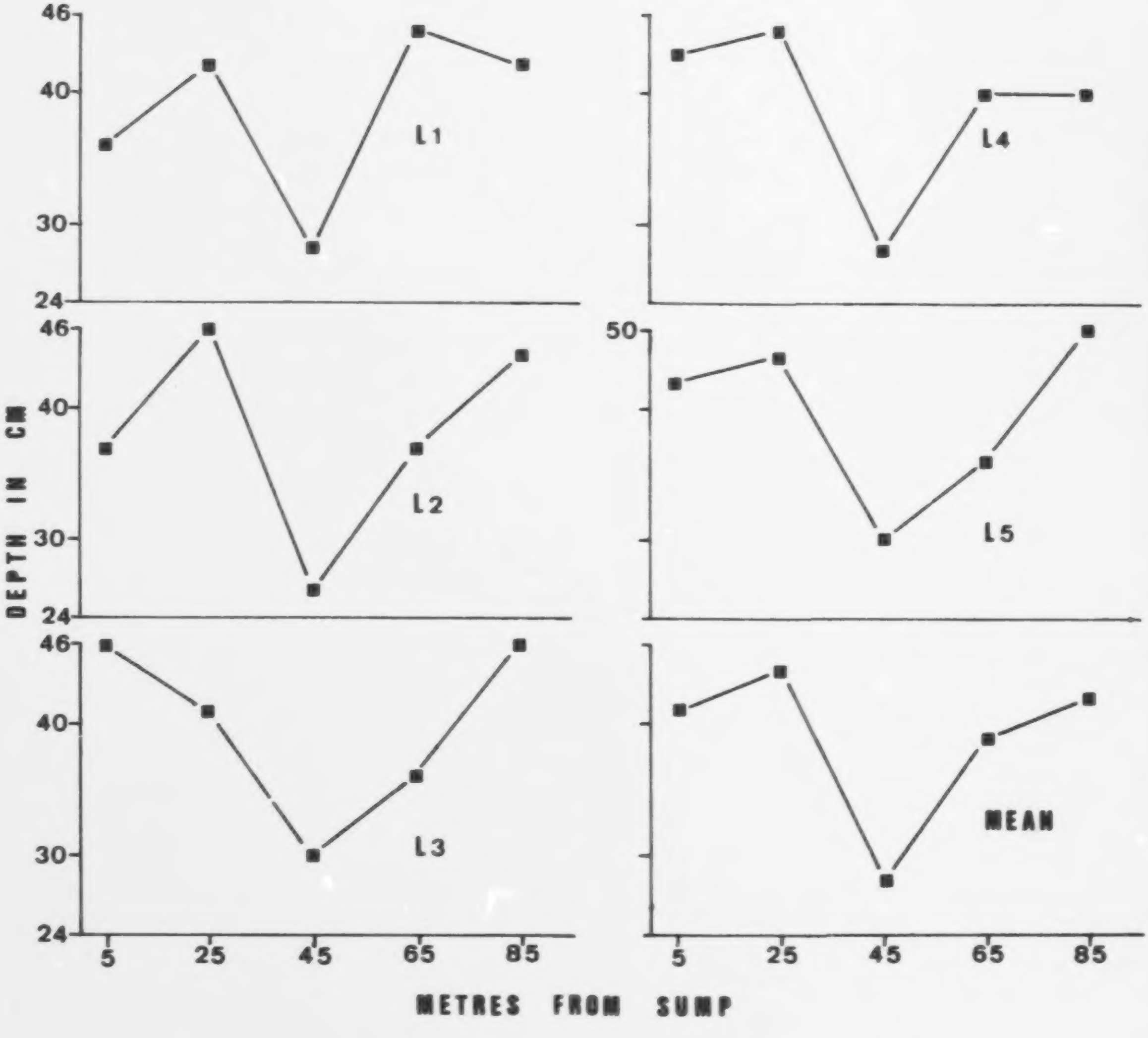


Figure 19. Active layer depth at Charles Point G-07 (measured on July 18, 1977).

movement along the front of the berm. Thermal effects of drilling activities, however, were mainly confined to the well lease.

The frost-table was closest to the surface at 45 m downslope from the sump at the base of a shallow slope. Increased insulating vegetation cover coupled with higher levels of soil moisture probably accounted for reductions in active layer depth in this area. Depth of thaw was generally greater than at Cape Fleetwood L-21 (also on sandy soils) possibly due to differences in surface albedo (surface soils were darker at Charles Point G-07), and subsurface characteristics.

5.3.3 Soil ion content:

Mean concentrations of acetate-extractable potassium at all soil depths downslope of the sump were not significantly different from background levels (Table 13). There was some evidence of slightly elevated levels at 0-5 cm depth between 5 m and 25 m from the sump (ca. 197% of background), but this trend was inconclusive. Surface potassium concentrations slightly higher than background at 85 m from the sump (Fig. 20) may have resulted from contamination due to seismic drilling. Some piles of rock cuttings were present in this area but they were not extensive. Potassium containing compounds were not major constituents of the drilling mud system (Table 13), hence low concentrations of this cation in soil were expected.

A trend of decreasing levels of extractable sodium with increasing distance downslope from the sump was evident throughout the active layer (Table 13). This trend was highly significant at soil depths of 0-5 cm. Mean sodium concentrations at the surface between 5 m and 25 m from the sump were approximately 1,596% of background. Concentrations of this cation in the same area at 15-20 cm soil depth were approximately 729% of background levels. These results indicated that appreciable soil contamination by sodium-rich drilling fluids had occurred at Charles Point G-07. The area of contamination at the soil surface was quite small covering less than 25% of the sample grid (Fig. 21). At 15-20 cm soil depth, high levels of sodium were only recorded at three points in the sample grid (Fig. 21). Concentrations of this cation at the base of the active layer were only marginally different from background (Table 13).

Exchangeable levels of soil barium and manganese downslope of the sump were very low and, in the main, were only slightly different from background (Table 13). There was some correlation between higher concentrations of barium and proximity to the sump at soil depths of 0-20 cm; however, mean levels at 5-45 m from the sump were only 121% of background. A similar trend was evident with soil manganese at 0-5 cm depth between 5 m and 25 m from the

Table 13. Mean concentrations (with standard errors) of extractable cations and chloride in soil at Charles Point G-07

Soil depth (cm)	Concentration (mg/100 g) at distance from sump (m)					
	5	25	45	65	85	UD
POTASSIUM						
0 - 5	6.9 ± 1.1	6.5 ± 1.4	4.6 ± 0.6	3.8 ± 0.8	5.1 ± 1.1	3.4 ± 0.1
15 - 20	3.6 ± 0.5	3.2 ± 0.2	4.1 ± 0.7	3.0 ± 0.7	3.2 ± 0.5	3.2 ± 0.2
P + 5	4.1 ± 0.7	2.9 ± 0.4	1.9 ± 0.9	2.8 ± 0.6	3.2 ± 0.5	3.0
SODIUM						
0 - 5 *	52.0 ± 21.1	31.0 ± 8.0	8.8 ± 1.2	16.9 ± 7.7	8.9 ± 3.6	2.6 ± 0.4
15 - 20	14.6 ± 7.3	10.2 ± 3.7	7.8 ± 2.2	6.4 ± 3.4	3.4 ± 1.1	1.7 ± 0.5
P + 5	7.0 ± 3.3	3.1 ± 0.3	4.8 ± 1.7	3.8 ± 1.0	2.9 ± 0.8	1.5 ± 1.1
BARIUM						
0 - 5	0.46 ± 0.05	0.56 ± 0.07	0.45 ± 0.05	0.36 ± 0.06	0.61 ± 0.11	0.43 ± 0.11
15 - 20	0.46 ± 0.09	0.47 ± 0.05	0.51 ± 0.09	0.32 ± 0.06	0.39 ± 0.03	0.37 ± 0.18
P + 5	0.50 ± 0.07	0.47 ± 0.05	0.51 ± 0.11	0.33 ± 0.07	0.42 ± 0.05	0.50 ± 0.21
MANGANESE						
0 - 5	0.46 ± 0.10	0.33 ± 0.03	0.28 ± 0.02	0.23 ± 0.04	0.23 ± 0.03	0.14 ± 0.03
15 - 20	0.16 ± 0.03	0.20 ± 0.04	0.32 ± 0.07	0.16 ± 0.03	0.15 ± 0.03	0.07 ± 0.02
P + 5 *	0.15 ± 0.03	0.13 ± 0.03	0.33 ± 0.08	0.15 ± 0.03	0.25 ± 0.06	0.07 ± 0.005
COPPER						
0 - 5	0.25 ± 0.11	0.05 ± 0.10	0.11 ± 0.05	0.06 ± 0.02	0.04 ± 0.01	0.05 ± 0.005
15 - 20	0.16 ± 0.06	0.07 ± 0.01	0.30 ± 0.21	0.07 ± 0.02	0.11 ± 0.04	0.03 ± 0.005
P + 5	0.17 ± 0.07	0.20 ± 0.08	0.30 ± 0.19	0.19 ± 0.06	0.18 ± 0.08	0.03 ± 0.005
ZINC						
0 - 5 *	0.75 ± 0.38	0.10 ± 0.03	0.13 ± 0.06	0.08 ± 0.02	0.06 ± 0.01	0.08 ± 0.04
15 - 20	0.30 ± 0.14	0.11 ± 0.05	0.12 ± 0.03	0.07 ± 0.02	0.08 ± 0.02	0.06 ± 0.02
P + 5	0.24 ± 0.11	0.14 ± 0.06	0.12 ± 0.05	0.08 ± 0.02	0.07 ± 0.01	0.05
CHLORIDE						
0 - 5	125 ± 31	131 ± 42	109 ± 2	136 ± 21	109 ± 3	106 ± 1
15 - 20	130 ± 24	117 ± 10	109 ± 4	105 ± 2	104 ± 1	105 ± 1
P + 5	117 ± 12	104 ± 1	97 ± 1	103 ± 2	104 ± 2	106 ± 1

*anova significant at $P_{0.05}$ level   UD - undisturbed area   P - frost-table

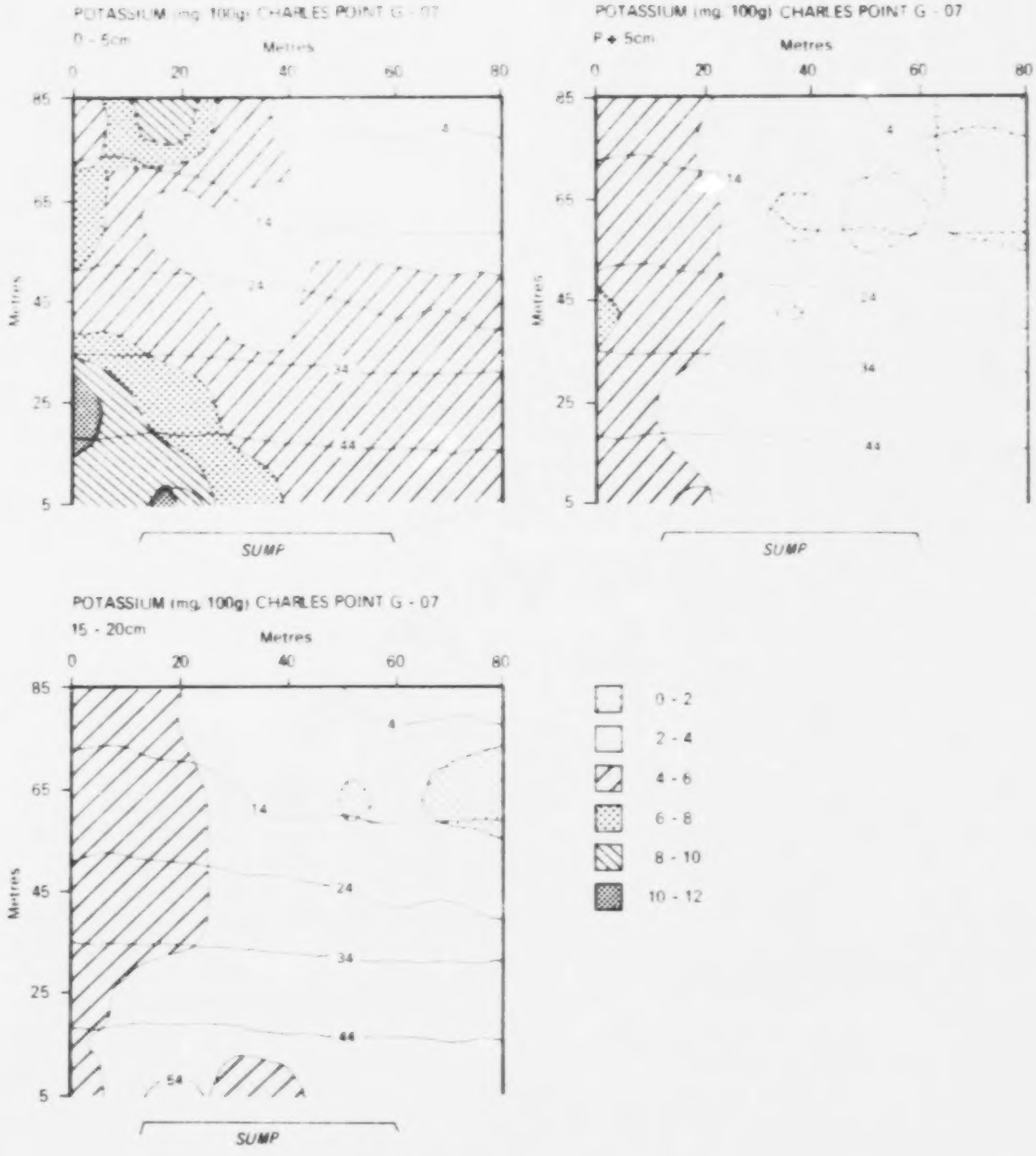

POTASSIUM (mg 100g) CHARLES POINT G - 07
0 - 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
4
14
24
34
44
SUMP
POTASSIUM (mg 100g) CHARLES POINT G - 07
P + 5cm
Metres
4
14
24
34
44
SUMP
POTASSIUM (mg 100g) CHARLES POINT G - 07
15 - 20cm
Metres
4
14
24
34
44
54
SUMP
0 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 12

Figure 20. Potassium concentrations in soil at Charles Point G-07.

Contour intervals are in dm and P+5 cm -- 5 cm above the frost-table.

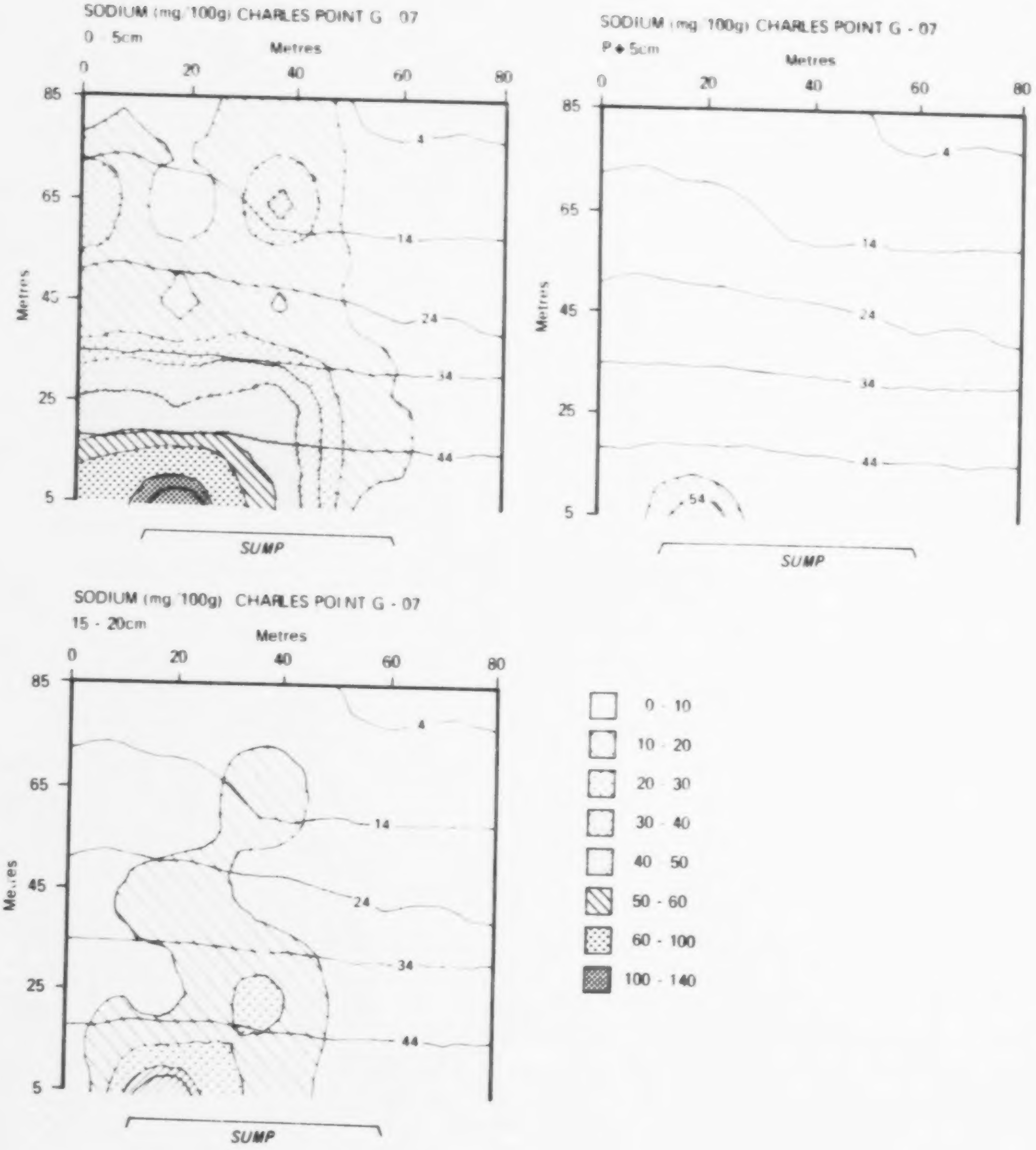

SODIUM (mg/100g) CHARLES POINT G - 07
0 - 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
4
14
24
34
44
SUMP
SODIUM (mg/100g) CHARLES POINT G - 07
P + 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
4
14
24
34
44
54
SUMP
SODIUM (mg/100g) CHARLES POINT G - 07
15 - 20cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
4
14
24
34
44
SUMP
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 100
100 - 140

Figure 21. Sodium concentrations in soil at Charles Point G-07.

Contour intervals are in dm and P±5 cm -- 5 cm above the frost-table.

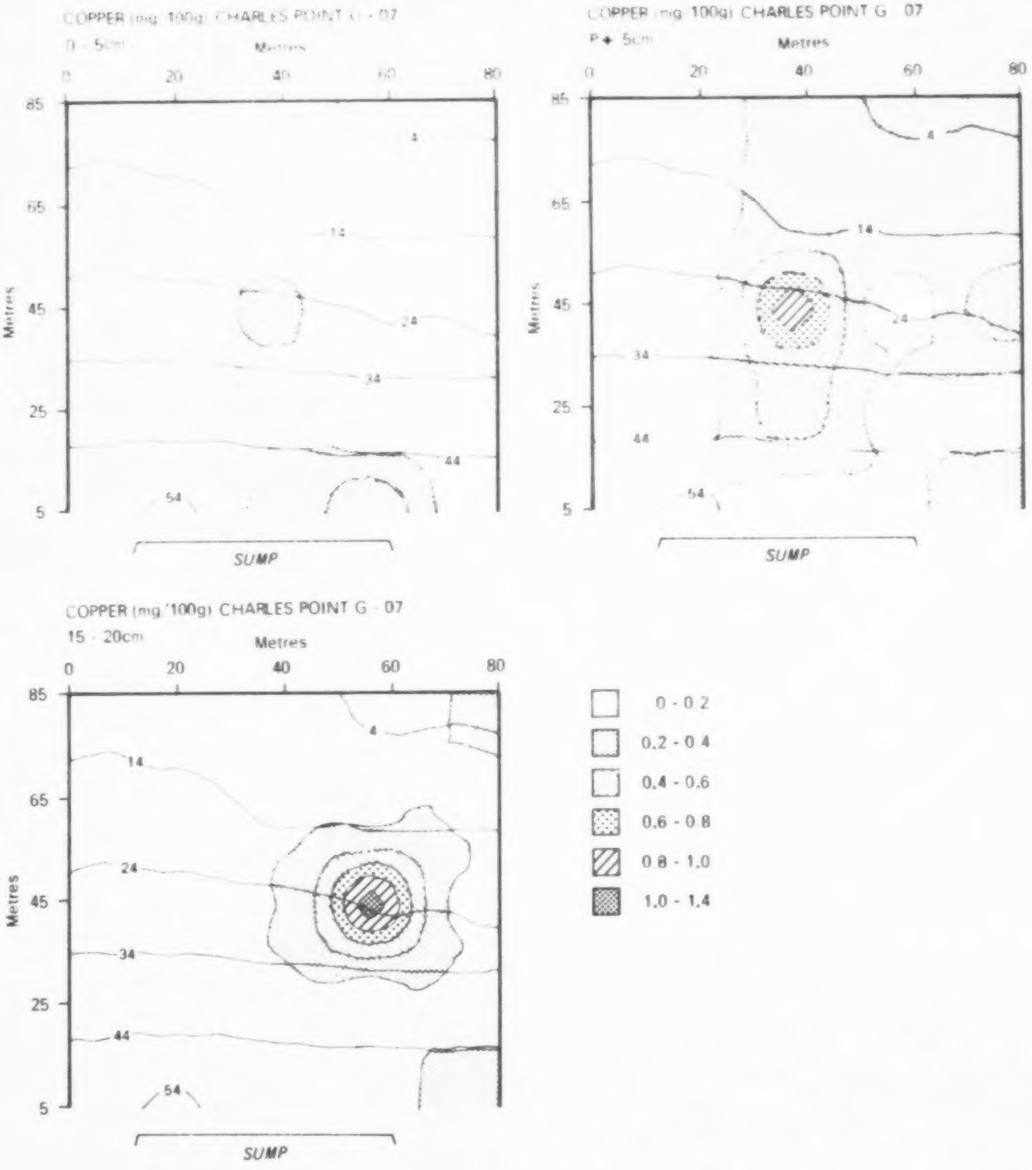

COPPER (mg/100g) CHARLES POINT G - 07
0 - 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
4
14
24
34
44
54
SUMP
COPPER (mg/100g) CHARLES POINT G - 07
P + 5cm
Metres
SUMP
COPPER (mg/100g) CHARLES POINT G - 07
15 - 20cm
Metres
SUMP
0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1.0
1.0 - 1.4

Figure 22. Copper concentrations in soil at Charles Point G-07.

Contour intervals are in dm and P+5 cm -- 5 cm above the frost-table.

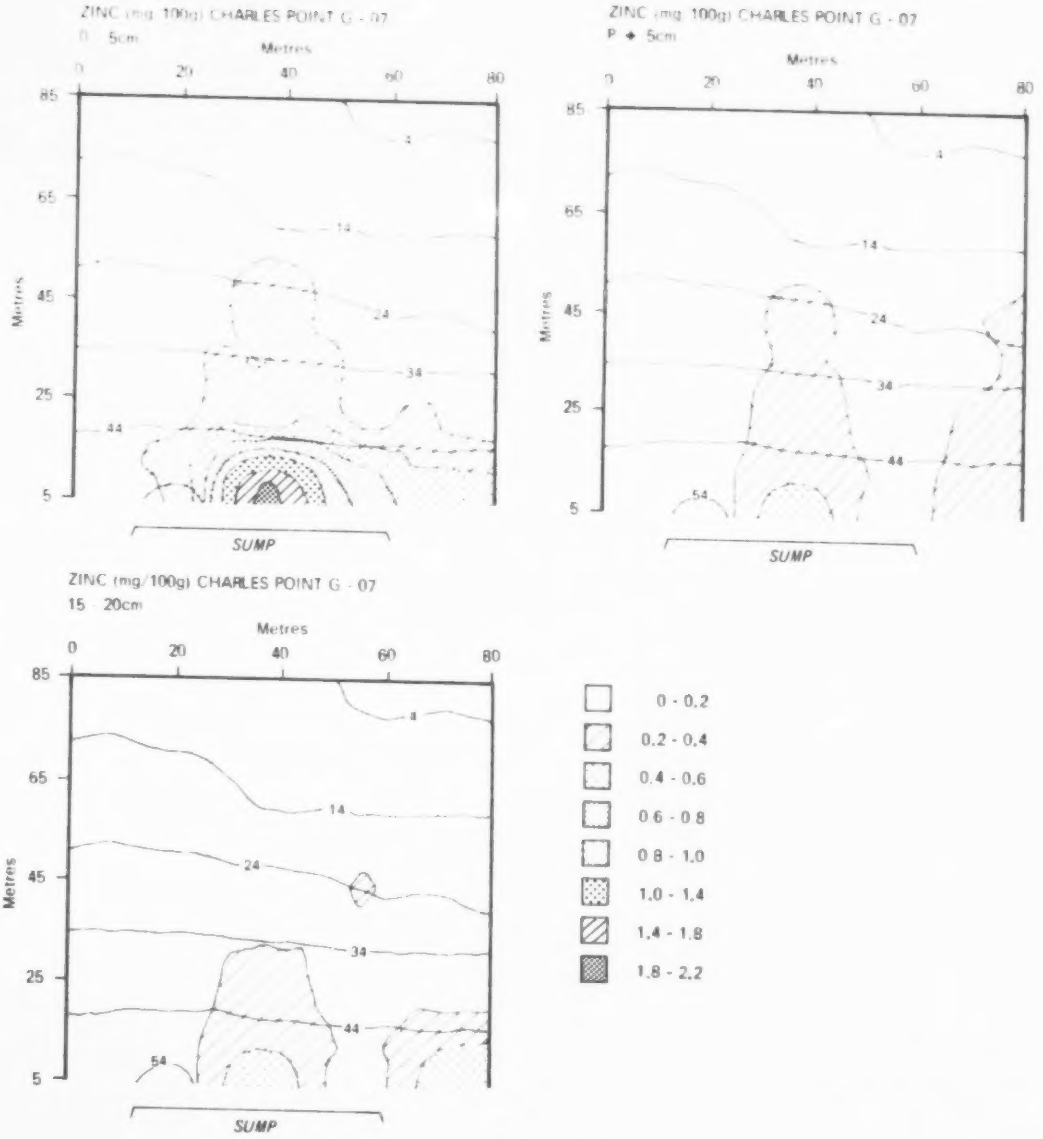

ZINC (mg/100g) CHARLES POINT G - 07
0 - 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
4
14
24
34
44
SUMP
ZINC (mg/100g) CHARLES POINT G - 07
P + 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
4
14
24
34
44
54
SUMP
ZINC (mg/100g) CHARLES POINT G - 07
15 - 20cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
4
14
24
34
44
54
SUMP
0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1.0
1.0 - 1.4
1.4 - 1.8
1.8 - 2.2

Figure 23. Zinc concentrations in soil at Charles Point G-07.

Contour intervals are in dm and P+5 cm
-- 5 cm above the frost-table.

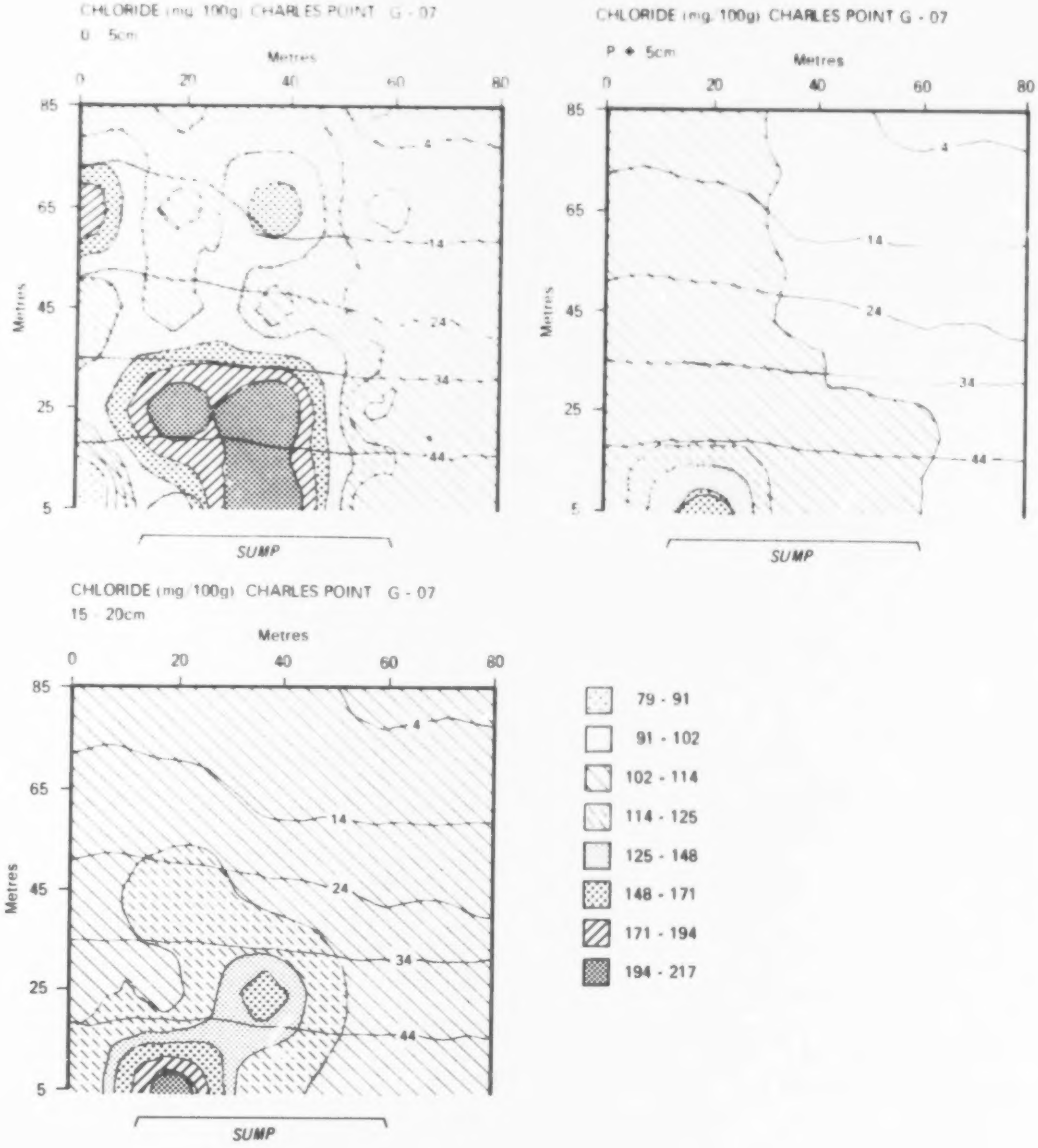

CHLORIDE (mg/100g) CHARLES POINT G - 07
0 - 5cm
CHLORIDE (mg/100g) CHARLES POINT G - 07
P + 5cm
CHLORIDE (mg/100g) CHARLES POINT G - 07
15 - 20cm
Metres
0
20
40
60
80
85
65
45
25
5
4
14
24
34
44
SUMP
79 - 91
91 - 102
102 - 114
114 - 125
125 - 148
148 - 171
171 - 194
194 - 217

Figure 24. Chloride concentrations in soil at Charles Point G-07.

Contour intervals are in dm and P+5 cm
-- 5 cm above the frost-table.

sump (levels were ca. 282% of background), but the area of elevated soil manganese was small. Relatively high concentrations of manganese in soil at 45 m from the sump probably reflected increases in organic content with the more complete plant cover at the base of the beach ridge.

Acetate-extractable levels of soil copper, although low, showed some correlation with distance from the sump. Mean levels at soil depths of 0-20 cm immediately adjacent to the sump were approximately 513% of background (Table 13). Downward movement of copper through the soil was indicated by its concentration in the basal 5 cm of the active layer. Mean concentrations across the sample area at this depth were approximately 820% of background and levels up to 600% of background occurred at distances of 85 m downslope from the sump (Table 13).

The particularly high levels of soil copper at single sampling points 45 m from the sump at 15-20 cm depth and immediately above the frost-table (Fig. 22) did not appear correlated with any surface features. Presumably, build-up of copper at these points was a product of subsurface drainage or soil physical-chemical characteristics.

Extractable zinc diminished throughout the active layer at increasing distances downslope from the sump indicating that contamination of soil by zinc containing drilling fluids had occurred at Charles Point G-07. This trend was highly significant at 0-5 cm soil depth (Table 13). Mean concentrations of zinc adjacent to the sump at soil depths of 0-5 cm, 15-20 cm and at the base of the active layer were 938%, 500% and 480% of background respectively.

The mean level throughout the active layer 25-45 m from the sump was 190% of background. Available zinc in the main was concentrated at the soil surface. The lateral and downslope extent of severe contamination at 0-5 cm was not great (Fig. 23), but within a small area some very high concentrations were recorded (maximum 2,750% of background). Zinc contamination of soil at 15-20 cm depth and immediately above the frost-table was quite restricted in area (Fig. 23).

Slight contamination of soil by chloride in drilling fluids was indicated by elevated levels of this ion close to the sump (Table 13). However, this trend was not significant and mean concentration of extractable chloride at 0-20 cm soil depth between 5 m and 25 m from the sump was only 119% of background. Some chloride contamination was evident in soil immediately above the frost-table but it was very restricted in extent (Fig. 24). Relatively high background levels of chloride at this site (Table 13) may have been related to the marine beach origin of the undisturbed soils.

5.3.4 Soil pH:

Soil pH in undisturbed areas at Charles Point G-07 was acidic throughout the active layer (Table 14). Surface soils (0-5 cm) downslope of the sump were slightly acidic but pH significantly tended towards neutral at soil depths of 15-20 cm and immediately above the frost-table at distances of 45 m to 85 m from the sump (Table 14, Fig. 25). This latter trend was difficult to relate to spillage of drilling mud materials. It may, however, have been a function of subsurface changes in soil drainage at the base of the beach ridge.

5.3.5 Surface water ion content:

Salt contamination of surface water in pools on the sump infill was indicated by potassium, sodium and chloride levels of 20.8, 240.0 and 2,375.0 mg/l respectively. Unfortunately, no background measurements were taken and comparison with other sites is not feasible due to differences in substrate. Levels of cadmium, chromium, zinc, copper, lead and manganese in pools on the sump surface ranged from 0-0.01 mg/l and were not significant.

5.3.6 Vegetation distribution:

Percentage frequencies of plant species recorded at Charles Point G-07 are listed in Table 15. Species richness of the vegetation was largely unaffected by drilling at this site. Compared to undisturbed areas, a reduction (20%) in number of species was evident 5 m from the sump but this was slight.

Occurrence of most species was reduced in the highly disturbed area within 5-10 m of the sump berm (Table 15). Species frequencies increased markedly at 25 m downslope. At distances of 45-85 m from the sump the frequencies of many species, especially the lichens, were similar to values in undisturbed areas. Disturbance-resistant species occurring with relatively high frequencies close to the sump included Pertusaria dactylina (Ach.) Nye., Thamnolia subuliformis, Alopecurus alpinus and Luzula spp. No species increased in occurrence immediately adjacent to the berm, although frequencies of some species were higher at 45 m than at greater distances downslope (Table 15).

Minimal disturbance of the vegetation at Charles Point G-07 was indicated by similar VDI values for the undisturbed and most below sump locations (Table 15). Disturbance mainly occurred adjacent to the sump berm. VDI at 5 m from the sump was 42% less than VDI for the undisturbed area (Table 15). The lower VDI for the undisturbed location compared to VDI at 85 m from the sump was due to reduced species richness. This presumably

Table 14. Mean soil pH (with standard errors) at Charles Point G-07

Soil depth (cm)		pH at distance from sump (m)				
	5	25	45	65	85	UD
0 - 5	6.5 ± 2.9	6.6 ± 1.5	6.7 ± 1.5	6.6 ± 1.7	6.3 ± 1.3	5.7 ± 0.4
15 - 20 *	6.2 ± 2.2	6.4 ± 1.9	7.3 ± 0.7	7.1 ± 2.3	6.9 ± 1.5	6.4 ± 0.5
P + 5 *	6.5 ± 2.6	6.8 ± 2.5	7.4 ± 1.8	7.4 ± 1.1	7.3 ± 1.3	6.8 ± 0.4

*anova significant at $P_{0.05}$ UD - undisturbed area P - frost-table

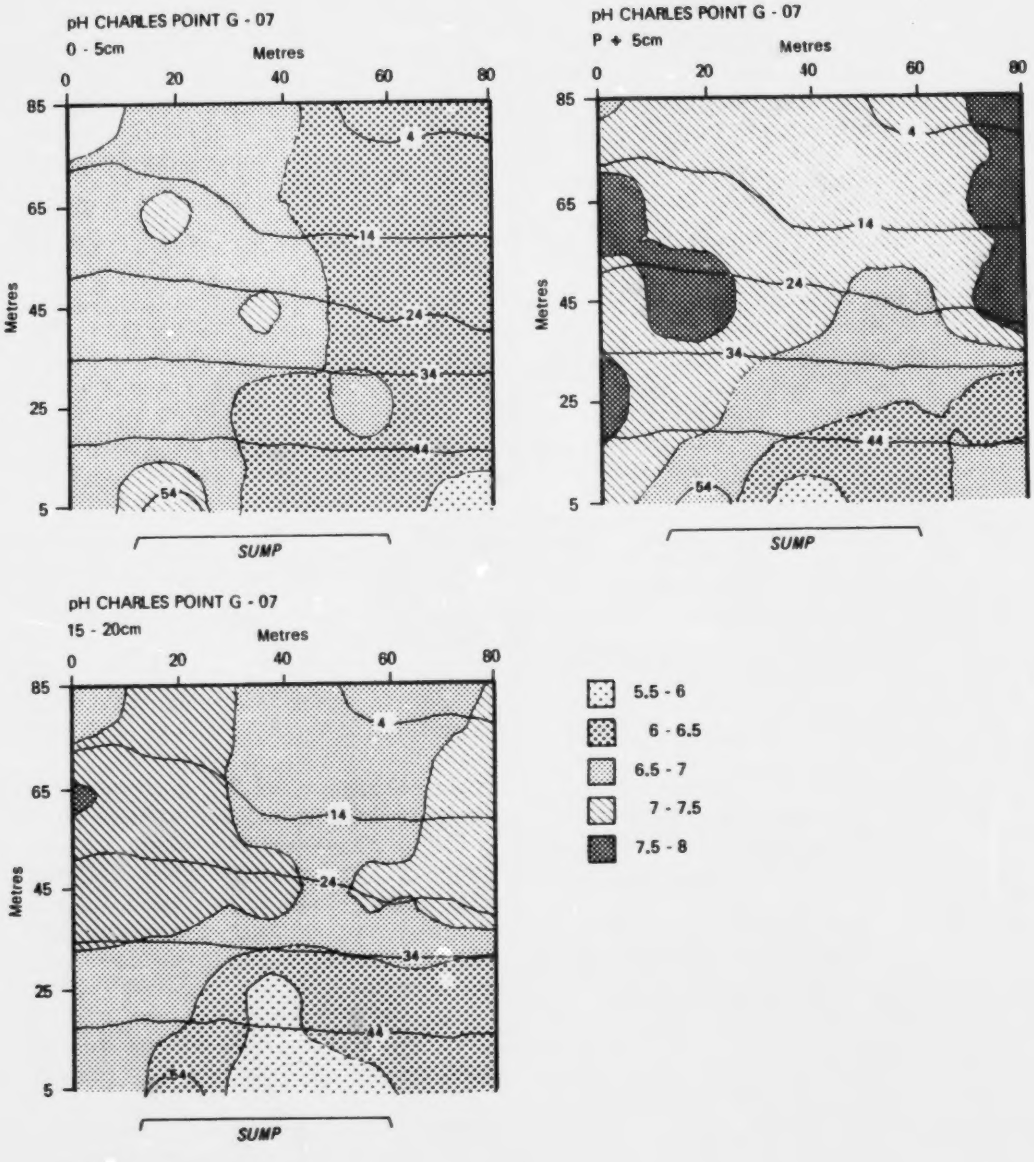

pH CHARLES POINT G - 07
0 - 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
4
14
24
34
44
54
SUMP
pH CHARLES POINT G - 07
P + 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
4
14
24
34
44
54
SUMP
pH CHARLES POINT G - 07
15 - 20cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
4
14
24
34
44
54
SUMP
5.5 - 6
6 - 6.5
6.5 - 7
7 - 7.5
7.5 - 8

Figure 25. Soil pH at Charles Point G-07.

Contour intervals are in dm and P+5 cm
-- 5 cm above the frost-table.

Table 15. Percentage frequency of plant species at Charles Point G-07 (UD -- undisturbed vegetation)

Species	Distance from sump (m)					
	5	25	45	65	85	UD
MOSSES						
Ditrichum flexicaule			15	45	70	100
Pogonatum alpinum var. septentrionale	5	60	50	65	95	100
Dead moss	85	90	100	100	100	100
LICHENS						
Cetraria cucullata	10	60	100	85	90	100
Cetraria delisei		50	100	90	85	100
Cetraria tilesii		45	100	65	85	13
Parmelia omphalodes	20	95	100	95	100	100
Pertusaria dactylina	70	100	100	90	100	100
Pseudephebe pubescens		25	85	80	65	50
Thamnolia subuliformis	75	95	100	100	100	100
Lichen sp.		5	15		45	
HIGHER PLANTS						
Alopecurus alpinus	50	50		60	80	50
Cardamine bellidifolia	25	80	80	50	80	100
Cerastium regelii			15			
Draba alpina	20	75	80	50	80	75
Draba corymbosa		90	60	60	90	25
Festuca brachyphylla					10	
Luzula sp.	55	100	75	100	100	100
Minuartia rossii		45	60	45	85	
Oxyria digyna	5	35	20	10	15	
Papaver radicatum	15	90	85	40	80	100
Potentilla hyparctica		25	20	25	80	63
Ranunculus sulphureus		25	20	20	30	75
Saxifraga caespitosa	15	55	75	50	95	
Saxifraga flagellaris ssp. platysepala					5	
Saxifraga nivalis	20	60	60	60	95	100
Saxifraga oppositifolia	15	20	65	55	75	
Saxifraga rivularis	25	100	85	90	90	100
Stellaria monantha	20	45	50	45	30	100
VDI	18	52	59	54	70	60

VDI - vegetation disturbance index (%)

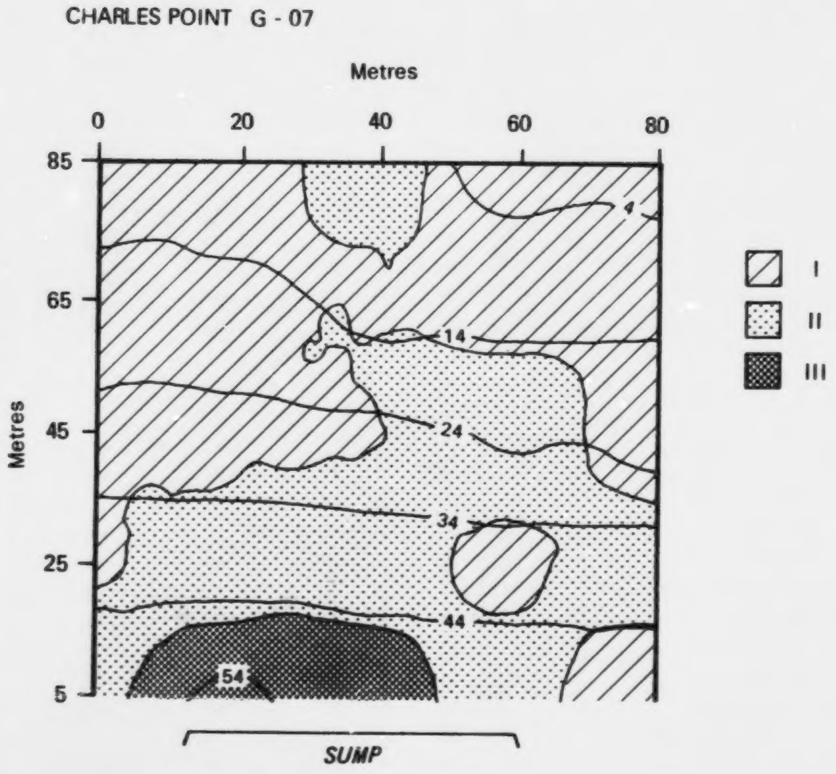

CHARLES POINT G - 07
Metres
0
20
40
60
80
85
65
45
25
5
Metres
4
14
24
34
44
54
SUMP
I
II
III

Figure 26. Community disturbance (CD) class map of Charles Point G-07.

Contour intervals are in dm and vegetation ranges from least disturbed (Class I) to most disturbed (Class IV).

reflected slight microsite differences, e.g. slightly more acidic surface soil in the undisturbed area (Table 14) and the higher and more exposed topographic position.

Axis 1 in the reciprocal averaging analyses accounted for 35% of the variability in species incidence at Charles Point G-07. There was some distribution of sample points on axis 2, accounting for 14% of the residual variance. The two axes in combination extracted 49% of the variability in species incidence data.

The most disturbed CD class III vegetation was restricted to within 15 m of the sump (Fig. 26). Vegetation disturbance by vehicle movement and overburden burial was widespread in this area. Levels of soil sodium, zinc and chloride were also high. Intermediately disturbed vegetation (CD class II) was widely distributed between 5 m and 50 m downslope from the sump (Fig. 26). There was no obvious correlation between occurrence of CD class II and soil ion content. Some scarification was evident at 15-25 m from the sump but effects on the vegetation were slight. Much of the vegetation between 45 m and 85 m appeared undisturbed (CD class I).

5.3.7 Ion content of plants:

Levels of sodium, zinc, lead and chloride in some of the dominant plant species at Charles Point G-07 are given in Table 16.

Gradients of increasing sodium content with proximity to the sumps were well defined in Alopecurus alpinus and Papaver radicatum. Sodium concentration in Alopecurus 5 m from the sump was 1,269% of background. Levels of this cation in Papaver growing at 25 m downslope were 1,324% of tissue concentrations at 85 m. Sodium levels in Luzula spp. and Saxifraga oppositifolia were high throughout the sample grid but gradients of increasing concentration with proximity to salt contaminated areas were poorly defined.

Chloride concentrations in Alopecurus alpinus growing close to the sump were 279% of background. Relatively high chloride levels also occurred in Luzula spp. and Saxifraga oppositifolia growing in contaminated soils. Tissue concentrations in the latter between 5 m and 65 m from the sump averaged 241% of levels recorded at 85 m downslope.

Lead concentrations in Saxifraga oppositifolia 5 m from the sump were 425% of background. However, levels of lead in most species were quite low and showed little correlation with drilling fluid contaminated soil. Luzula spp. contained relatively high amounts of lead close to the sump, but background levels were also high. Luzula spp. growing in contaminated areas also appeared to concentrate zinc. Gradients of increasing zinc in the other dominants with proximity to the sump were not strongly evident.

Table 16. Concentrations (mg/100 g) of total sodium, zinc, lead and chloride in plant species at Charles Point G-07 (UD -- undisturbed area)

Species	Distance from sump (m)					
	5	25	45	65	85	UD
SODIUM						
Alopecurus alpinus	501.3			140.8		39.5
Luzula sp.	202.5	340.0			168.3	27.5
Papaver radicatum		1,680.0	465.9	38.4	126.9	
Saxifraga oppositifolia	185.0	345.0	176.7	326.6	47.8	
ZINC						
Alopecurus alpinus	9.8			10.0		10.5
Luzula sp.	14.5	9.5			12.1	2.0
Papaver radicatum			10.7	8.8	9.8	
Saxifraga oppositifolia	8.0	7.6	6.6	6.5	7.0	
LEAD						
Alopecurus alpinus	5.0			3.5		trace
Luzula sp.	10.2	3.9			8.3	9.0
Papaver radicatum		9.2	5.5	8.7	3.2	
Saxifraga oppositifolia	10.2	3.1	3.3	3.0	2.4	
CHLORIDE						
Alopecurus alpinus	7,423.4			3,138.8		2,664.9
Luzula sp.	1,811.9	5,145.9			3,247.6	2,380.6
Papaver radicatum			2,211.5	1,881.6	2,772.9	
Saxifraga oppositifolia	2,285.8	3,127.7	2,365.0	1,712.0	984.6	

Plate 4.

Air view of Robert Harbour K-07 showing proximity of site to natural watercourse, drilling mud spill near the wellhead, and gully crossing sump infill to the right of mud spill.

Surface spill of drilling mud (dark grey areas) near the wellhead at Robert Harbour K-07.

5.4 Robert Harbour K-07

5.4.1 Site description and well history:

Robert Harbour K-07 (76° 36' 32.20"N 104° 02' 14.10"W) is located on semi-polar desert terrain at the northern end of Cameron Island (Fig. 1a). Landform is regionally a coastal plain and the well is situated on a flat beach 2-3 km from the present shoreline. Soils are sands with a low proportion of silt. The drainage pattern is dendritic.

K-07 was drilled to a final depth of 3,805 m. The well was spudded on April 26, 1974 and completed on August 17, 1974. Two mud systems were employed in the drilling operation (depths are in metres):

0 - 368	Salt gel system
368 - 3,805	Fresh gel - Kelzan X-C polymer system

Total quantities of solid mud components, liquid components (excluding water) and washing agents used are listed in Table 17. Both freshwater and saltwater were used in the drilling operation.

Drilling mud wastes and rig wash were discharged to a sump of dimensions ca. 41 m x 31 m x 3 m excavated in well-drained sand. The sump was located on slightly sloping terrain (0°-2° slope) immediately adjacent to a natural watercourse (Fig. 27). Sump infill material was sand derived from the original excavation. No sump problems developed during drilling but land-use inspectors reported (August 12, 1975) that drilling fluids had squeezed out of the sump after infilling.

Extensive slumping of infill was observed over the whole sump area in July 1977. A gully approximately 1 m deep and 3 m wide had been eroded across the sump (Plate 4). Sand fill and drilling mud had been washed via this gully into the larger adjacent watercourse (Plate 4). This watercourse (included in the sample grid) drained directly into the Arctic Ocean. Considerable salt and pink chemical deposits were evident on the sump surface and in the natural watercourse. A small spill of drilling mud, together with salt deposits, was also noted close to the well-head (Plate 4) but this did not directly affect the sample area.

Disturbance of unconsolidated sand materials was severe at Robert Harbour K-07. Rutting from heavy vehicle passage was extensive and vegetation on the lease area was practically non-existent. Extension of disturbance off the lease necessitated expanding the sample grid to 80 m x 100 m in order to sample relatively undisturbed vegetation. The main causes of vegetation disturbance within the sample grid (0-50 m downslope of the sump) appeared to be burial by sand overburden, scarification of the soil surface, and chemical

Table 17. Total quantities of solids and liquids (excluding water) discharged to well sump at Robert Harbour K-07

Product	Description	Quantity
	SOLIDS	KILOGRAMS
Barite	Barium sulphate	225,227
Bentonite	Montmorillonite clay	59,091
	Salt gel	5,864
Kelzan X-C polymer	Xanthan gum	12,818
Peltex	Ferro-chrome lignosulphonate	750
Caustic soda	Sodium hydroxide	5,420
Lime	Calcium hydroxide	386
Dowicide B	Sodium trichlorophenate	161
	Aluminium stearate	130
	Sodium bicarbonate	273
C.M.C.	Sodium carboxymethyl cellulose	273
	Gypsum	645
Plaster of Paris	Fine gypsum	1,409
	Chrome alum	2,077
TOTAL		314,524
	LIQUIDS	LITRES
Magobar		114
	Diesel fuel	10,490
	Crude oil	4,053
Pipelax		295
Sparto Ep		358
TOTAL		15,310

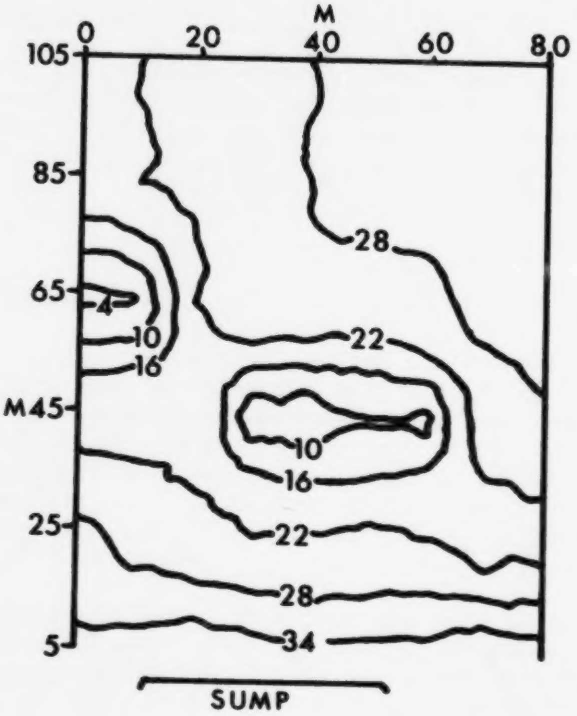

M
0
20
40
60
80
105
85
65
M45
25
5
28
22
4
10
16
10
16
22
28
34
SUMP

Figure 27. Topography at Robert Harbour K-07
(contour intervals in dm).

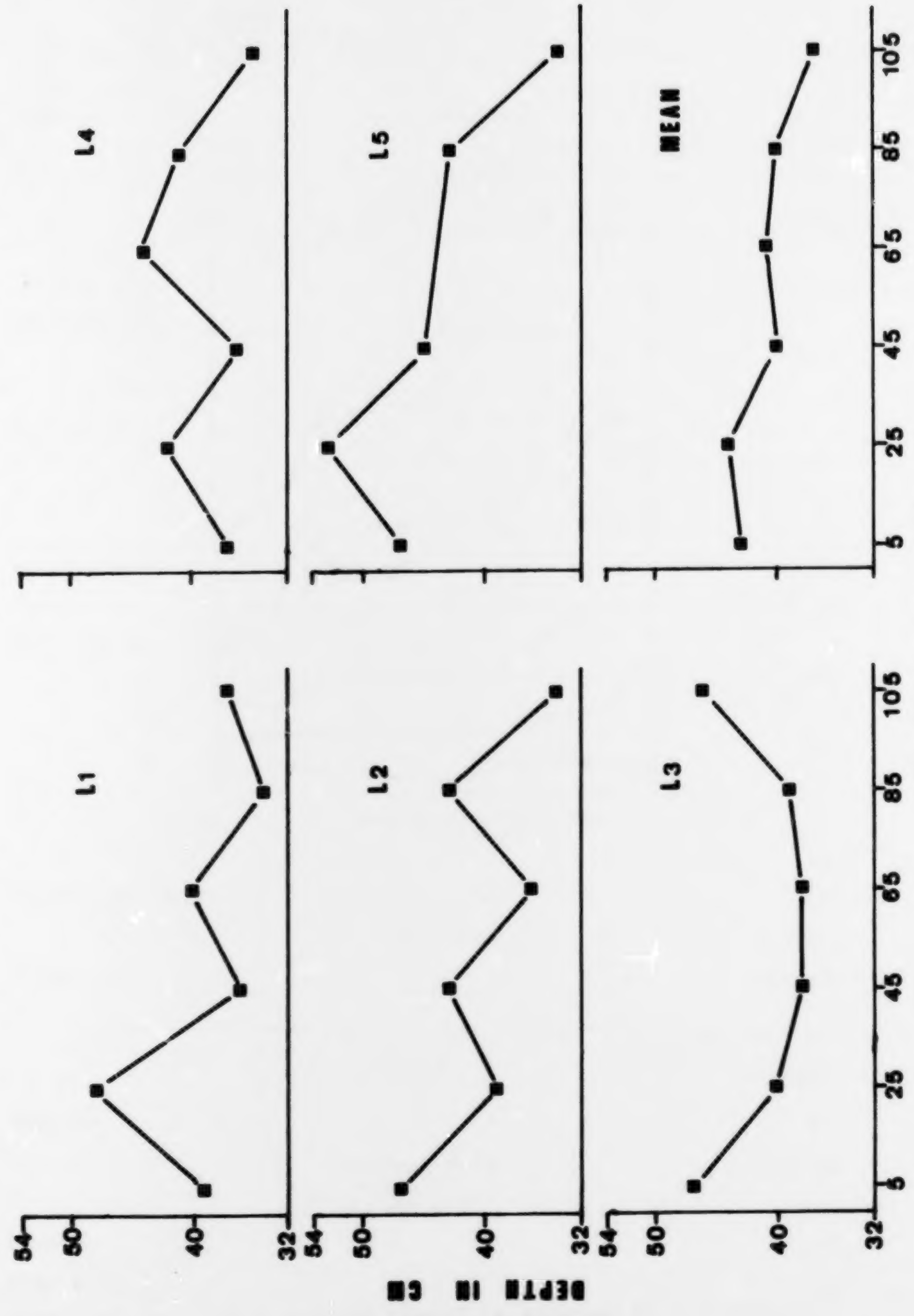


Figure 28. Active layer depth at Robert Harbour K-07 (measured on July 20, 1977).

contamination (salt deposits were extensive). Very few plants were present in severely disrupted areas adjacent to the sump. The main recolonizers in this zone were *Oxyria digyna*, *Alopecurus alpinus* and *Luzula* spp. Plant cover in undisturbed areas was approximately 20% to 30%.

5.4.2 Active layer depth:

Although thaw depth in mid-July varied along individual sample grid lines at Robert Harbour K-07 (Fig. 28), mean depth to the frost-table did not significantly change with distance from the sump. There was some indication of slight increases in active layer depth close to the downslope berm but this did not seem to be related to drilling activities.

5.4.3 Soil ion content:

Extractable potassium at the soil surface was concentrated close to the sump and in a natural watercourse 45 m downslope from the berm (Fig. 29). Mean surface concentration 5 m from the sump was 213% of background (Table 18) with individual values ranging up to 463% of background. Mean potassium levels in the watercourse were slightly less (ca. 180% of background); however, they indicated that some downslope movement of potassium-rich drilling fluids had occurred at Robert Harbour K-07.

Accumulations of potassium 25-45 m from the berm at soil depths of 15 cm to the base of the active layer (Fig. 29) were further evidence of downslope migration of this ion from the sump. Mean levels 45 m from the berm (Table 18) were appreciably higher (ca. 213%) than at 85-100 m. This difference was statistically significant. Sample points at 105 m from the sump were on elevated ground beyond the watercourse. These areas were unaffected by potassium contamination (Fig. 29).

Amounts of potassium added to the drilling fluid as KCl (in the salt gel) were relatively high (Table 18) and this was reflected by high levels in spilled mud. Extractable potassium concentrations in the mud spill near the well-head were approximately 533% of background levels.

Exchangeable potassium concentrations were relatively high at all soil depths in the undisturbed area, (Table 18).

Extractable sodium diminished significantly with increasing distance from the sump at all soil depths (Table 18). Mean sodium concentration at the soil surface was 4,445% of background and over 7,000% in some places. Levels at 15-20 cm were 383% of background on average.

Table 18. Mean concentrations (with standard errors) of extractable cations and chloride in soil at Robert Harbour K-07

Soil depth (cm)	Concentration (mg/100 g) at distance from sump (m) 5	25	45	65	85	105	UD
POTASSIUM							
0 - 5	17.9 ± 2.7	9.5 ± 1.4	15.1 ± 6.2	8.9 ± 1.5	6.5 ± 1.1	7.0 ± 0.7	8.4 ± 3.3
15 - 20*	8.9 ± 1.6	9.7 ± 2.1	16.3 ± 4.3	7.7 ± 0.7	4.5 ± 0.5	5.6 ± 0.5	12.7 ± 3.5
P + 5 *	7.4 ± 2.0	14.9 ± 1.7	14.2 ± 5.5	6.6 ± 0.7	4.5 ± 1.4	4.9 ± 0.6	11.6 ± 4.6
SODIUM							
0 - 5 *	106.7 ± 31.9	19.9 ± 4.1	70.5 ± 29.5	11.6 ± 6.4	7.3 ± 3.5	4.1 ± 1.2	2.4 ± 1.3
15 - 20*	19.9 ± 6.7	28.1 ± 9.7	37.4 ± 13.7	7.3 ± 3.8	3.7 ± 1.4	3.2 ± 1.6	5.2 ± 0.8
P + 5 *	6.8 ± 1.2	17.3 ± 2.6	48.7 ± 24.5	7.3 ± 4.4	3.6 ± 1.7	1.9 ± 0.5	5.1 ± 2.6
BARIUM							
0 - 5 *	2.3 ± 0.6	3.0 ± 0.9	1.3 ± 0.7	0.4 ± 0.1	0.3 ± 0.1	0.3 ± 0.1	0.7 ± 0.2
15 - 20	0.5 ± 0.2	0.4 ± 0.09	0.5 ± 0.1	0.4 ± 0.1	0.3 ± 0.1	0.4 ± 0.2	0.3 ± 0.2
P + 5	0.4 ± 0.1	0.8 ± 0.2	1.0 ± 0.4	0.3 ± 0.1	0.4 ± 0.1	0.2 ± 0.08	0.6 ± 0.1
MANGANESE							
0 - 5	0.76 ± 0.30	0.60 ± 0.15	0.57 ± 0.30	0.20 ± 0.02	0.24 ± 0.07	0.24 ± 0.04	0.16 ± 0.08
15 - 20	0.24 ± 0.04	0.44 ± 0.06	0.55 ± 0.21	0.26 ± 0.06	0.12 ± 0.02	0.15 ± 0.02	0.11 ± 0.02
P + 5	0.15 ± 0.01	0.27 ± 0.03	0.47 ± 0.15	0.21 ± 0.04	0.12 ± 0.03	0.13 ± 0.01	0.11 ± 0.03
ZINC							
0 - 5	0.03 ± 0.01	0.01 ± 0.003	0.02 ± 0.002	0.02 ± 0.01	0.01 ± 0.01	0.01	0.02 ± 0.01
15 - 20	0.03 ± 0.01	0.02 ± 0.004	0.02 ± 0.01	0.17 ± 0.14	0.05 ± 0.04	0.01 ± 0.002	0.01 ± 0.01
P + 5	0.01 ± 0.002	0.01 ± 0.003	0.01 ± 0.004	0.03 ± 0.02	0.02 ± 0.01	0.04 ± 0.03	0.03 ± 0.02
LEAD							
0 - 5	0.13 ± 0.04	0.07 ± 0.02	0.12 ± 0.06	0.10 ± 0.03	0.14 ± 0.02	0.09 ± 0.02	0.03 ± 0.02
15 - 20	0.07 ± 0.02	0.06 ± 0.02	0.10 ± 0.03	0.09 ± 0.03	0.12 ± 0.02	0.09 ± 0.03	0.03 ± 0.03
P + 5	0.07 ± 0.02	0.07 ± 0.03	0.08 ± 0.02	0.08 ± 0.03	0.11 ± 0.02	0.08 ± 0.02	0.02 ± 0.02
CHLORIDE							
0 - 5	242 ± 104	119 ± 4	146 ± 21	119 ± 6	132 ± 25	112 ± 7	109 ± 7
15 - 20	138 ± 19	134 ± 16	153 ± 26	111 ± 5	105 ± 3	103 ± 3	110 ± 5
P + 5	106 ± 4	116 ± 2	204 ± 74	108 ± 3	105 ± 3	104 ± 2	110 ± 4

*anova significant at $P_{0.05}$ level UD - undisturbed area P - frost-table

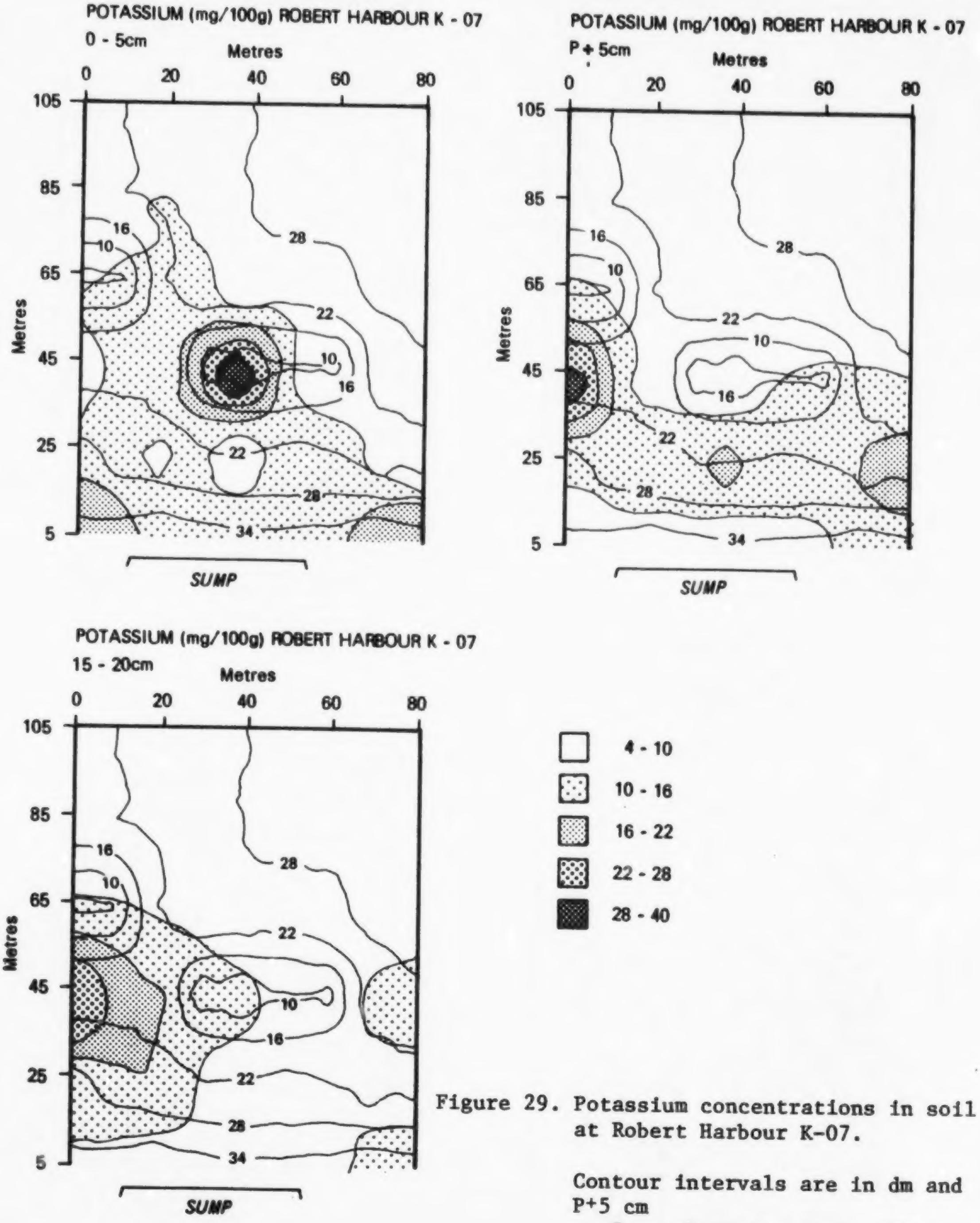

POTASSIUM (mg/100g) ROBERT HARBOUR K - 07
0 - 5cm
POTASSIUM (mg/100g) ROBERT HARBOUR K - 07
P + 5cm
POTASSIUM (mg/100g) ROBERT HARBOUR K - 07
15 - 20cm
Metres
0
20
40
60
80
105
85
65
45
25
5
10
16
22
28
34
SUMP
4 - 10
10 - 16
16 - 22
22 - 28
28 - 40

Figure 29. Potassium concentrations in soil at Robert Harbour K-07.

Contour intervals are in dm and P+5 cm
-- 5 cm above the frost-table.

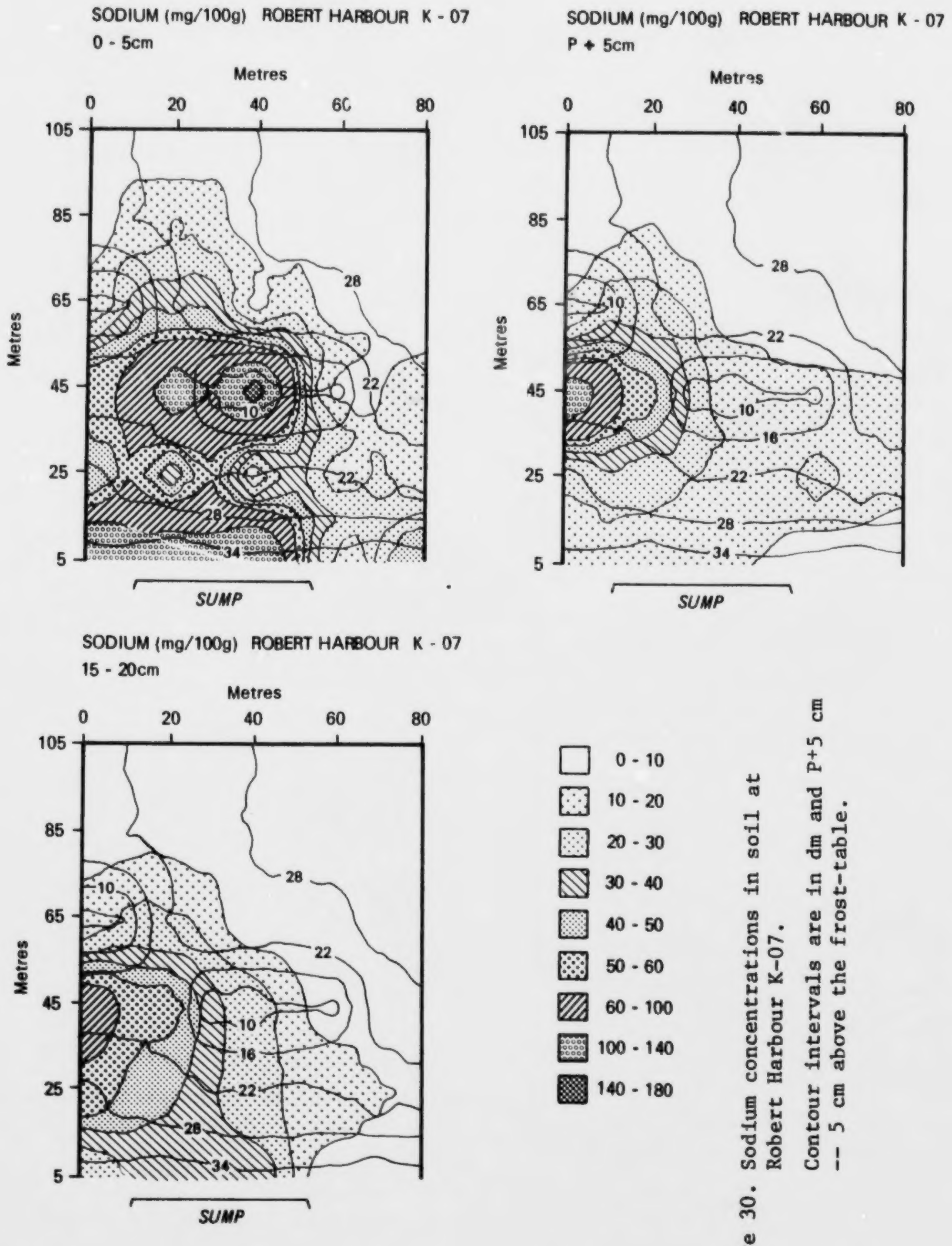

SODIUM (mg/100g) ROBERT HARBOUR K - 07
0 - 5cm
Metres
0
20
40
60
80
105
85
65
45
25
5
Metres
28
22
10
22
28
34
SUMP
SODIUM (mg/100g) ROBERT HARBOUR K - 07
P + 5cm
Metres
10
28
22
10
16
22
28
34
SUMP
SODIUM (mg/100g) ROBERT HARBOUR K - 07
15 - 20cm
Metres
10
28
22
10
16
22
28
34
SUMP
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 100
100 - 140
140 - 180

Figure 30. Sodium concentrations in soil at Robert Harbour K-07.

Contour intervals are in dm and P+5 cm -- 5 cm above the frost-table.

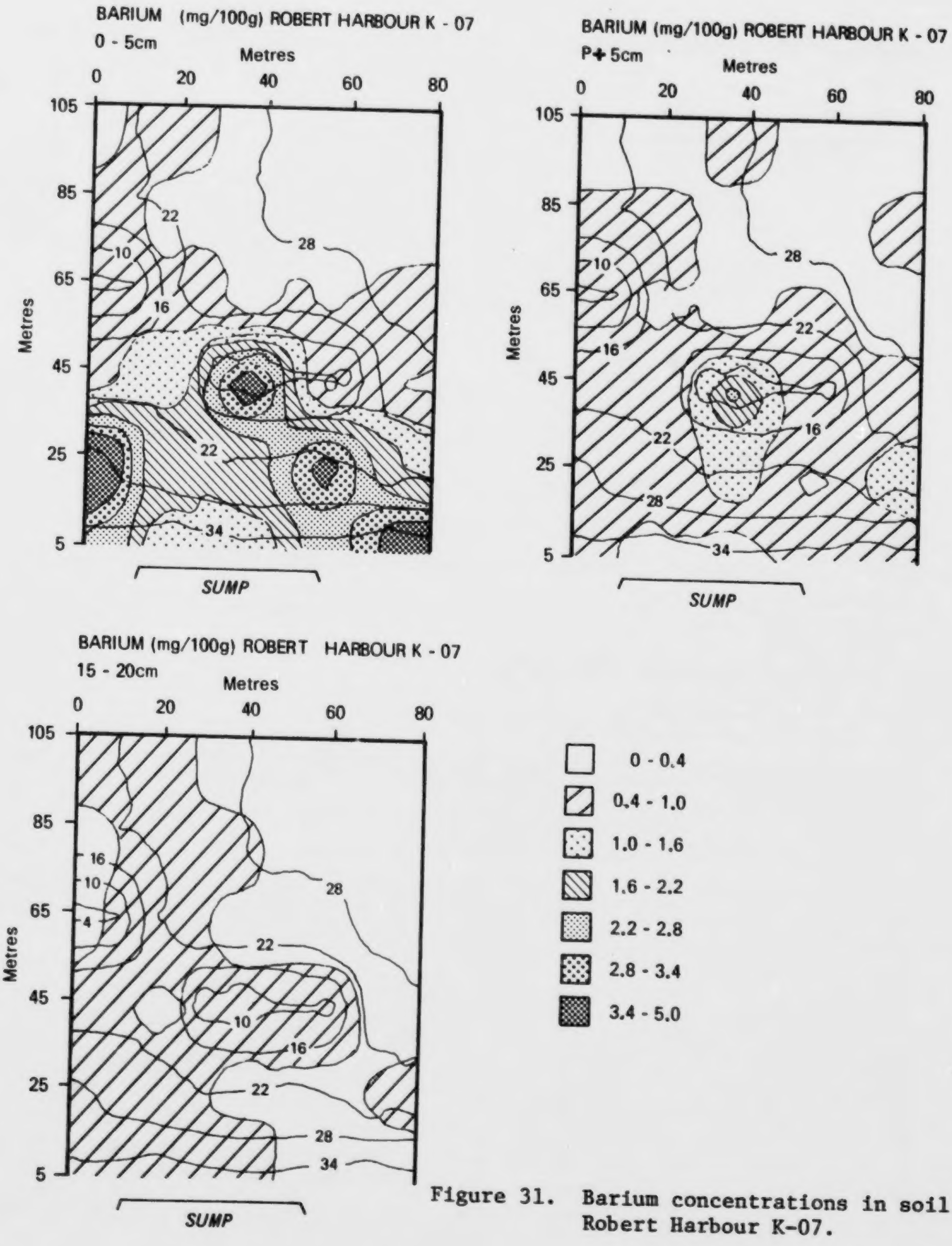

BARIUM (mg/100g) ROBERT HARBOUR K - 07
0 - 5cm
BARIUM (mg/100g) ROBERT HARBOUR K - 07
P+ 5cm
BARIUM (mg/100g) ROBERT HARBOUR K - 07
15 - 20cm
Metres
0
20
40
60
80
105
85
65
45
25
5
10
16
22
28
34
4
SUMP
0 - 0.4
0.4 - 1.0
1.0 - 1.6
1.6 - 2.2
2.2 - 2.8
2.8 - 3.4
3.4 - 5.0

Figure 31. Barium concentrations in soil at Robert Harbour K-07.

Contour intervals are in dm and P+5 cm
-- 5 cm above the frost-table.

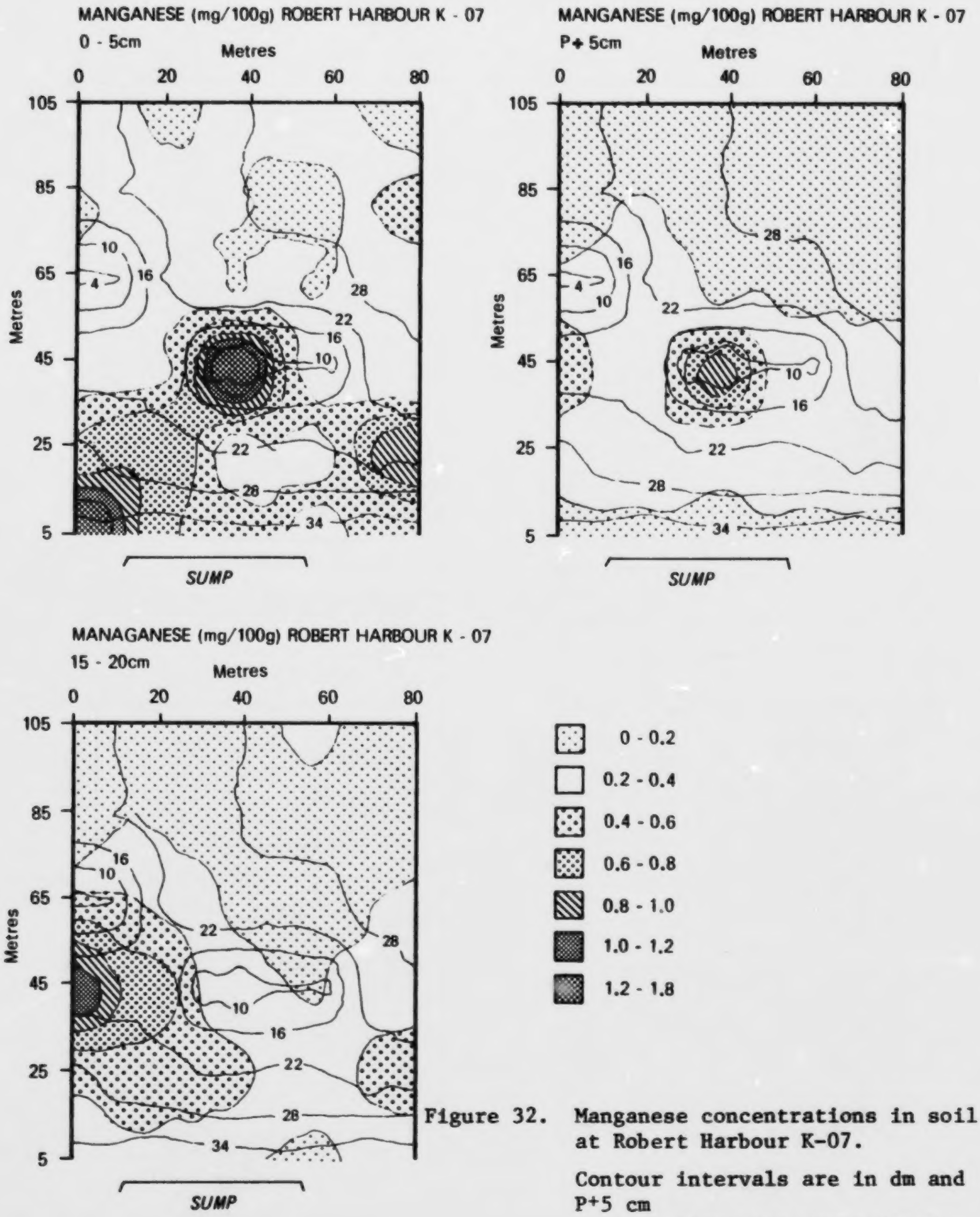
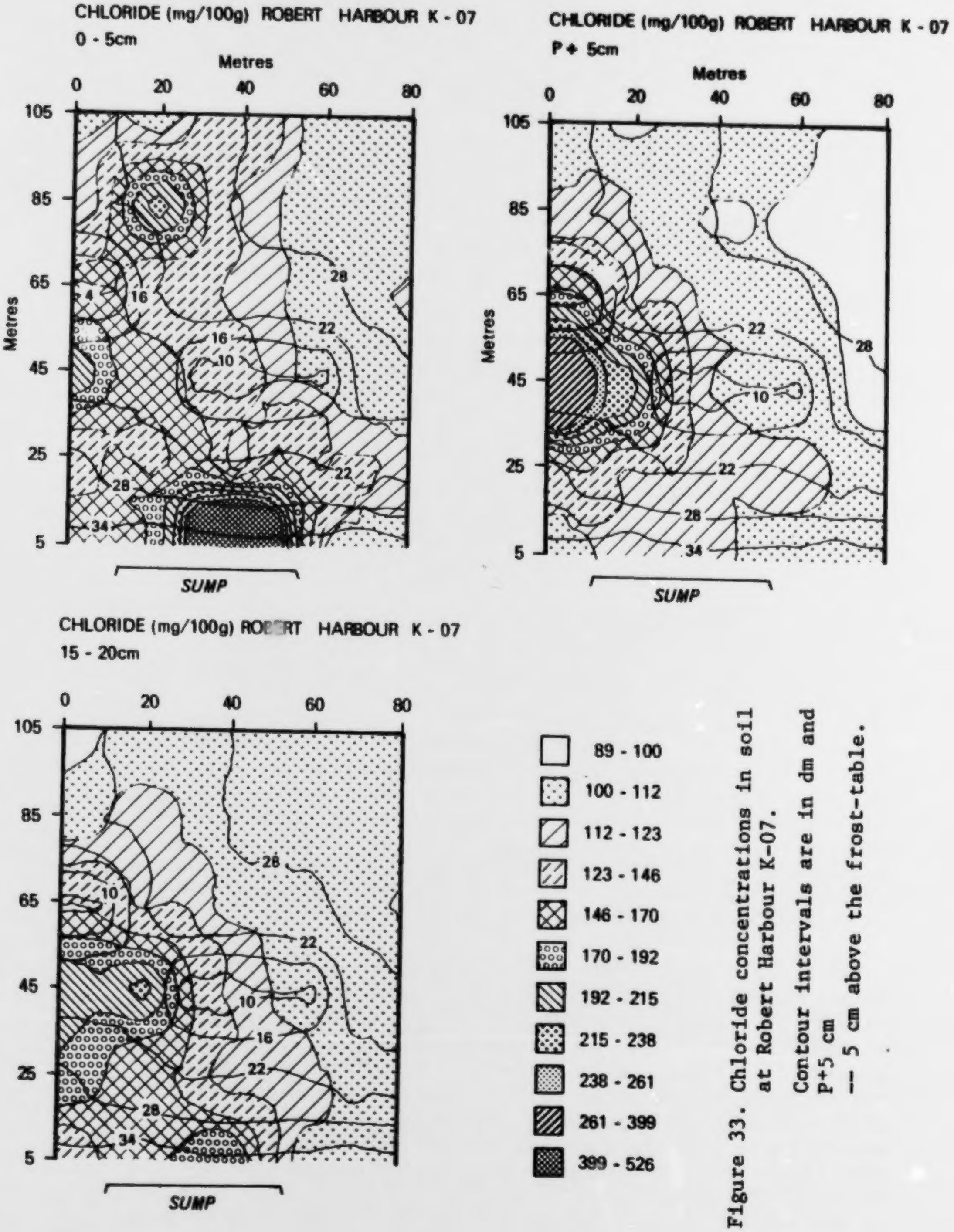

MANGANESE (mg/100g) ROBERT HARBOUR K - 07
0 - 5cm
Metres
0
20
40
60
80
105
85
65
45
25
5
Metres
10
4
16
28
22
16
10
22
28
34
SUMP
MANGANESE (mg/100g) ROBERT HARBOUR K - 07
P+ 5cm
Metres
28
16
4
10
22
10
16
22
28
34
SUMP
MANAGANESE (mg/100g) ROBERT HARBOUR K - 07
15 - 20cm
Metres
16
10
22
28
10
16
22
28
34
SUMP
0 - 0.2
0.2 - 0.4
0.4 - 0.6
0.6 - 0.8
0.8 - 1.0
1.0 - 1.2
1.2 - 1.8

Figure 32. Manganese concentrations in soil at Robert Harbour K-07.

Contour intervals are in dm and P+5 cm
-- 5 cm above the frost-table.



CHLORIDE (mg/100g) ROBERT HARBOUR K - 07
0 - 5cm

CHLORIDE (mg/100g) ROBERT HARBOUR K - 07
P + 5cm

CHLORIDE (mg/100g) ROBERT HARBOUR K - 07
15 - 20cm

Metres
0
20
40
60
80
105
85
65
45
25
5
4
10
16
22
28
34
SUMP
89 - 100
100 - 112
112 - 123
123 - 146
146 - 170
170 - 192
192 - 215
215 - 238
238 - 261
261 - 399
399 - 526

Figure 33. Chloride concentrations in soil at Robert Harbour K-07.

Contour intervals are in dm and P+5 cm — 5 cm above the frost-table.

Sodium was also concentrated in the watercourse 45 m downslope from the sump (Fig. 30). Mean values here ranged from 2,938% of background at the soil surface to 733% at 15 cm depth. Soil sodium concentrations at some points at the surface in this gully were over 6,500% of background.

Levels of extractable sodium in drilling mud spilled on the soil surface were 15,313% of background. These very high concentrations were somewhat surprising because sodium additions to the drilling fluid at Robert Harbour K-07 were less than at some other sites surveyed. Presumably, sodium enrichment from the saltwater component of the mud was responsible for the high values.

Substantial quantities of barium sulphate were added to the drilling mud (Table 18) but barium contamination of soil downslope of the sump was slight (Fig. 31). There was a significant increase in extractable barium levels at the soil surface with increasing proximity to the sump berm. Surface concentrations between 5 m and 25 m from the sump were 379% of background (Table 18). Concentrations of extractable barium in spilled mud were low (ca. 133% of background on average). Presumably, barium becomes tightly bound to the exchange sites on the montmorillonite clay added to the drilling fluids system.

Levels of extractable manganese were generally low (Table 18) but were higher than background over the entire sample grid at all soil depths. There was some evidence of manganese contamination from sump fluids, especially at 0-5 cm soil depth (Fig. 32). Manganese concentrations at this depth between 5 m and 25 m from the sump were approximately 425% of backgorund (Table 18). Manganese was also concentrated at all soil depths in the watercourse downslope of the sump. Mean levels at depths of 15 cm to the base of the active layer were approximately 464% of background at 45 m from the sump (Table 18). These trends, although not statistically significant, indicated some contamination of soil by manganese-rich drilling fluids. Manganese concentration in spilled drilling mud was 910% of background.

Extractable zinc levels in soil downslope of the sump were mainly comparable to background throughout the active layer (Table 18). High concentrations of this cation were only noted at 15-20 cm soil depth 65 m from the sump (ca. 1,700% of background on average). A concentration 6,900% above background was measured at one point in this area. There was no evidence of any correlation between concentration of zinc in the soil and distance from the sump and reasons for these high extractable zinc levels are not obvious. Soil contamination from spilled drilling fluids, however, is suspected. Extractable zinc levels in mud spilled on the surface were up to 5,000% of background.

Levels of acetate-extractable lead in soil downslope of the sump were higher than background but lead contamination was only strongly evident at depths of 0-5 cm. Mean lead concentration at the soil surface 5 m from the sump was 433% of background (Table 18). There was also some evidence of lead contamination of surface soil in the downslope watercourse. Concentrations of this heavy metal at 45 m to 85 m from the sump averaged 400% of background. Similar trends at soil depths extending from 15 cm to the base of the active layer were not as pronounced (Table 18). The pattern of lead distribution was not statistically significant. Concentrations of extractable lead in spilled mud averaged 600% of background.

Extractable levels of chromium and copper were insignificant, ranging from 0.03-0.004 mg/100 g. Downslope concentrations of these cations were no different from background levels and showed no variation with proximity to the sump.

Mean levels of extractable soil chloride at 0-5 cm depth (Table 18) show high concentrations of this ion occurring immediately adjacent to the sump. Chloride concentration at the soil surface 5 m from the sump berm was 221% of background with some individual values exceeding background by 500% (Fig. 33). Surface chloride levels were also slightly elevated (ca. 118% of background) at 25 m to 85 m from the sump but this trend was not significant. Extractable chloride at 15-20 cm soil depth between 5 m and 45 m from the sump was approximately 130% of background on average. Chloride at the base of the active layer was concentrated in the watercourse where mean levels were about 186% of background (Table 18). Extractable chloride in spilled drilling mud was 361% of background concentrations.

5.4.4 Soil pH:

Little variation in soil pH was apparent throughout the active layer downslope of the sump. There was some tendency for slightly higher pH values at all soil depths in the watercourse between 25 m and 85 m from the sump berm (Fig. 34), but this was insignificant (Table 19). Close correlation between high levels of exchangeable cations and soil pH was not evident at this site and the slightly alkaline soil appeared well-buffered. pH values in soil downslope from the sump were not appreciably different from background (Table 19).

5.4.5 Surface water ion content:

Water samples were collected from surface pools and streams in natural drainageways at Robert Harbour K-07. Ion levels measured in flowing water, upslope of the sump, were taken as background.

Table 19. Mean soil pH (with standard errors) at Robert Harbour K-07

Soil depth (cm)	pH at distance from sump (m)						
	5	25	45	65	85	105	UD
0 - 5	7.7 ± 0.2	8.1 ± 0.2	8.1 ± 0.2	7.9 ± 0.1	7.8 ± 0.1	7.8 ± 0.03	7.8 ± 0.01
15 - 20	7.7 ± 0.06	8.0 ± 0.2	7.8 ± 0.1	7.8 ± 0.04	8.1 ± 0.05	7.8 ± 0.05	7.7 ± 0.03
P + 5	7.9 ± 0.2	7.9 ± 0.08	8.1 ± 0.1	8.1 ± 0.06	8.3 ± 0.06	7.9 ± 0.05	7.9 ± 0.08

UD - undisturbed area P - frost-table

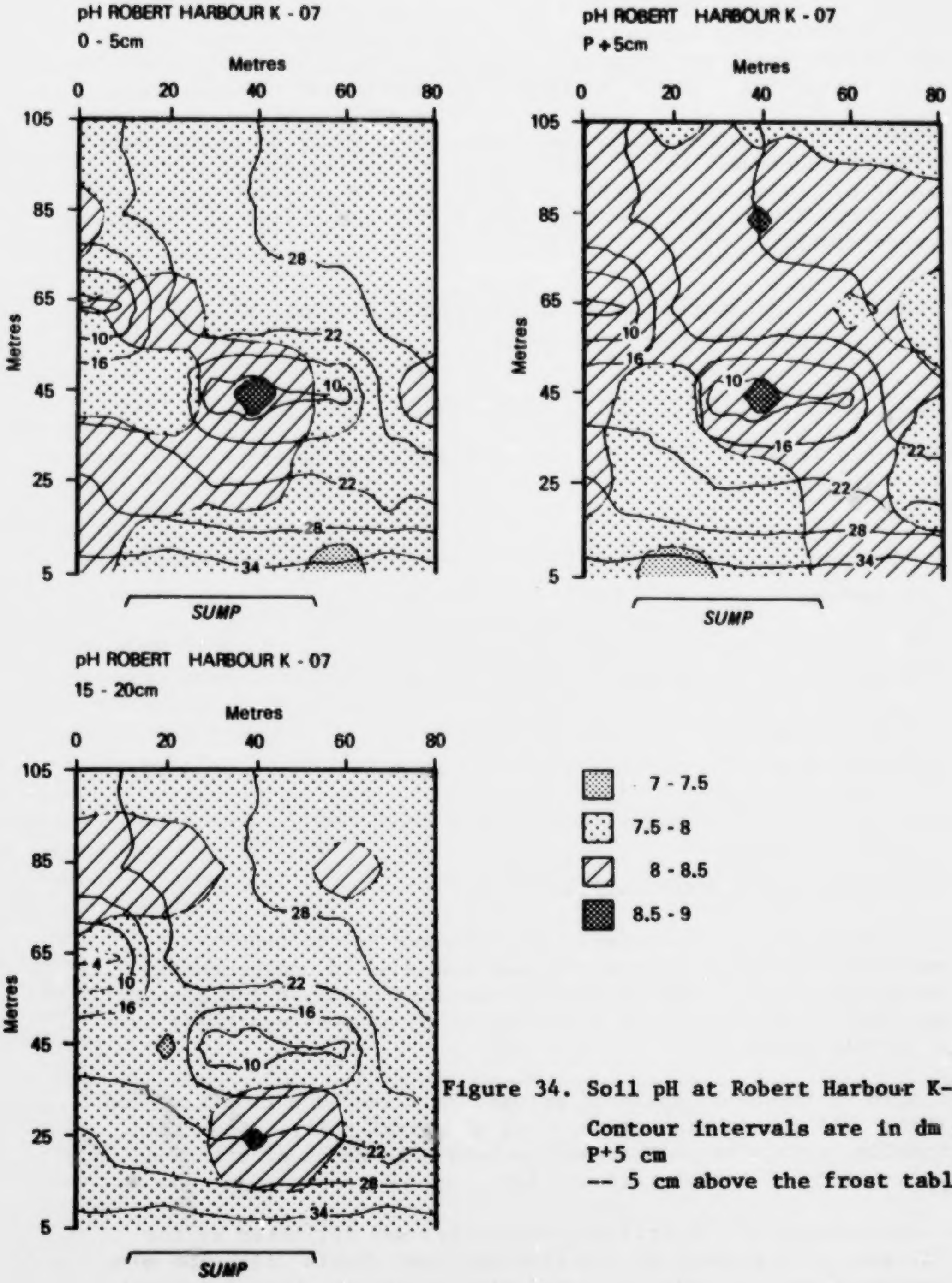

pH ROBERT HARBOUR K - 07
0 - 5cm
Metres
0
20
40
60
80
105
85
65
45
25
5
Metres
28
22
10
16
10
22
28
34
SUMP
pH ROBERT HARBOUR K - 07
P + 5cm
Metres
0
20
40
60
80
105
85
65
45
25
5
Metres
10
16
10
16
22
22
28
34
SUMP
pH ROBERT HARBOUR K - 07
15 - 20cm
Metres
0
20
40
60
80
105
85
65
45
25
5
Metres
28
4
10
22
16
16
10
22
28
34
SUMP
7 - 7.5
7.5 - 8
8 - 8.5
8.5 - 9

Figure 34. Soil pH at Robert Harbour K-07.

Contour intervals are in dm and P+5 cm
-- 5 cm above the frost table.

Concentrations of cadmium, chromium, zinc, copper, lead and manganese ranging from 0-0.05 mg/l were insignificant. There was no difference between levels of these cations in standing or flowing water and downslope concentrations were no different from background. Levels of potassium, sodium and chloride were high in standing water close to the sump and diminished downslope (Table 20). Concentration of potassium in pools 60 m downslope from the sump was 146% of background. Contamination of surface water by sodium and chloride at 60 m from the sump was appreciable. Downslope levels of these ions were 7,799% and 6,939% of background respectively.

Table 20. Ion content of standing (S) and flowing (F) water at Robert Harbour K-07

Distance from the sump (m)	Ion concentration (mg/l)		
	K	Na	Cl
35 upslope	5.1	8.0	117.1 (S)
200 upslope	8.9	6.9	61.3 (F)
400 upslope	11.1	9.0	66.9 (F)
60 downslope	14.6	620.0	4,449.0 (S)
150 downslope	13.8	11.5	75.3 (S)

5.4.6 Vegetation distribution:

Species richness was appreciably reduced in the heavily scarified zone 0-50 m from the sump compared to undisturbed areas (Table 21). The greatest reductions occurred immediately adjacent to the sump berm (48%) and at 65 m downslope (62%) in a natural gully.

Species frequency declined between 25 m and 50 m from the sump (Table 21) due to disruption along a natural gully. Some grid sampling points in this area coincided with pools of standing water empty of terrestrial species.

Disturbance due to drilling activities was reflected by the low species frequency at 5 m from the sump (Table 21). The more resistant species which occurred with relatively high frequencies in this area included *Alopecurus alpinus*, *Luzula* spp.,

Table 21. Percentage frequency of plant species at Robert Harbour K-07 (UD -- undisturbed vegetation)

Species	Distance from sump (m)						
	5	25	45	65	85	105	UD
MOSSES							
Ditrichum flexicaule	20	5	20	15	20	85	100
Pogonatum alpinum var. septentrionale	20		20	20	35	80	100
Dead moss	40	20	5	75	85	100	100
LICHENS							
Cetraria cucullata				35	30	50	63
Cetraria delisei				5		30	63
Cetraria tilesii		5			5	10	
Parmelia omphalodes	5	5		10	10	30	75
Pertusaria dactylina	20	20	5	20	45	80	100
Thamnolia subuliformis	5	15		30	55	75	100
HIGHER PLANTS							
Alopecurus alpinus	35	10		5	20	10	100
Cardamine bellidifolia				10		35	63
Cerastium regelii				5		20	25
Draba alpina		5		25	10	90	100
Draba corymbosa				5	5	80	100
Festuca brachyphylla	5	20	20	40	25	75	75
Luzula sp.	40	20		50	65	80	88
Minuartia rossii				20	15	75	88
Papaver radicatum	15	5	10	45	45	100	100
Saxifraga caespitosa						20	75
Saxifraga nivalis	5					25	63
Saxifraga oppositifolia			5	20	50	80	100
Saxifraga rivularis	25	15	5	30	10	45	88
Stellaria monantha			10	10	20	40	100
VDI	10	6	4	21	24	55	81

VDI - vegetation disturbance index (%)

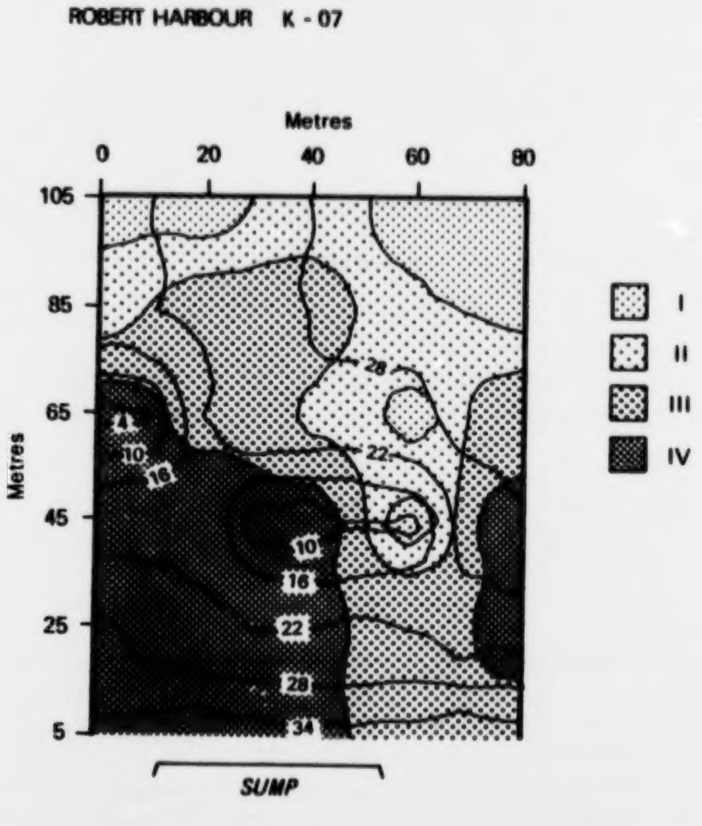

ROBERT HARBOUR K - 07
Metres
0
20
40
60
80
105
85
65
45
25
5
Metres
28
22
4
10
16
10
16
22
28
34
SUMP
I
II
III
IV

Figure 35. Community disturbance (CD) class map of Robert Harbour K-07.

Contour intervals are in dm and vegetation ranges from least disturbed (Class I) to most disturbed (Class IV).

and Saxifraga rivularis L. Occurrence of all species close to the sump was less than in undisturbed areas.

Reduced species frequency at 85 m and 105 m downslope compared to undisturbed areas (Table 21) was a result of vegetation disturbance along the perimeter of a landing strip. Disruption at this distance from the sump due to vehicle passage was generally slight.

VDI values were very low at all distances from the sump compared to the undisturbed VDI (Table 21). These low values reflected the effects of disturbance on both species richness and frequency. Lowest VDI values were at 25 m and 45 m downslope from the sump berm where effects of natural disturbance in a watercourse were compounded by disturbance associated with sump wall slumping and vehicle damage. Mean VDI values between 5 m and 45 m from the sump were 74% lower than VDI for the undisturbed area (Table 21). The effects of scarification due to vehicle passage on vegetation at 85-105 m from the sump were shown by the reduction in VDI values (58% on average) compared to the undisturbed VDI.

Axis 1 in the reciprocal average ordination accounted for 28% of the variation in species incidence. Axis 2 accounted for 15% of the remaining variance. A total of 42% of the variability in species incidence was extracted by axes 1 and 2.

The highly disturbed CD class IV vegetation was widespread in the area between 5 m and 65 m from the sump (Fig. 35). Levels of soil sodium and chloride were very high at some points in this area (Figs. 30 and 33) and vegetation burial by sand overburden washed from the sump was common. Intermediately disturbed (CD class III) vegetation occurred at some locations up to 85 m from the sump (Fig. 35). This distribution also seemed to be correlated with levels of various soil ions. CD classes II and I (the least disturbed vegetation) mainly occurred between 85 m and 105 m from the sump (Fig. 35). Overall, the CD map indicated that vegetation disturbance was widespread at Robert Harbour K-07. Natural disturbance in a downslope gully was extended and intensified by drilling activities.

5.4.7 Ion content of plants:

Sodium and chloride concentrations in Oxyria digyna and Saxifraga oppositifolia were relatively high in salt contaminated areas close to the sump compared to background and levels at 105 m downslope (Table 22). Concentrations of sodium in Oxyria 25 m downslope were 922% of levels recorded at 105 m. Tissue levels of sodium in Saxifraga oppositifolia adjacent to the sump berm were 879% of background. Gradients of decreasing chloride concentrations in these species with distance from salt-contaminated soils were less sharply defined (Table 22).

Table 22. Concentrations (mg/100 g) of total sodium, lead and chloride in plant species at Robert Harbour K-07 (UD -- undisturbed area)

Species	Distance from sump (m)					
	5	25	45	65	85	UD
SODIUM						
Ditrichum flexicaule			48.0	23.0	29.0	24.5
Oxyria digyna		830.0	167.5	64.5	90.0	
Papaver radicatum	90.0				24.4	26.8
Saxifraga oppositifolia	145.0		35.0	24.1	23.2	16.5
LEAD						
Ditrichum flexicaule			trace	3.9	3.2	6.5
Oxyria digyna		8.2	3.5	8.5	5.2	
Papaver radicatum	13.2				2.0	5.8
Saxifraga oppositifolia	9.5		trace	2.3	2.0	trace
CHLORIDE						
Ditrichum flexicaule			607.7	462.7	624.4	613.3
Oxyria digyna		2,715.1	1,890.0	685.8	1,878.8	
Papaver radicatum	1,850.9				1,678.1	1,683.7
Saxifraga oppositifolia	2,001.5		1,533.2	1,338.1	1,287.9	1,025.8

Papaver radicatum accumulated some sodium and chloride in its tissues in contaminated areas, but levels close to the sump were only slightly higher than background (Table 22). Salt concentrations in Ditrichum flexicaule between 65 m and 105 m downslope were close to background (Table 22).

Relatively high levels of lead occurred in Papaver radicatum and Saxifraga oppositifolia growing in drilling fluid contaminated soils (Table 22). Lead accumulations in Papaver at 5 m from the sump were 228% of background. Tissue levels of lead in the other dominants showed little variation with distance from the sump or from background.

5.5 Apollo C-73

5.5.1 Site description and well history:

Apollo C-73 (75° 32' 00.01"N 111° 58' 58.06"W) is located on an upland semi-polar desert plateau on central Melville Island (Fig. 1b). Soils are silts and clays with a high proportion of coarse shale fragments at the surface. Sorted polygon development, is not pronounced. Vegetation cover is sparse at about 5%.

The well is situated in a small but critical area comprising the northernmost summer breeding ground of the peregrine falcon, a rare and endangered species. It is also within the year-round range for an estimated 1,000 muskoxen which populate Melville Island. Muskoxen summer on the alluvial plains, tundra meadow, and associated wet meadow. Their winter range is semi-polar desert, especially upland slopes exposed to wind where snow cover is minimal (Arctic Ecology Map Series, 1972).

Apollo C-73 was drilled to a final depth of 3,696 m. The well was spudded on May 13, 1973 and completed on August 10, 1973. Amounts of solids used in drilling are listed in Table 23 together with total quantities of washing agents and liquid mud components (excluding water). Freshwater only was used in the drilling.

Drilling wastes and rig wash were discharged to a sump approximately 49 m x 46 m x 2 m excavated in poorly drained silts and clays. The original sump was located on slightly sloping terrain (Fig. 36), but slope angles of 6° and more occur a short distance from the site. Sump infill material was heavy clay mixed with stone.

Sump problems developed at Apollo C-73 during the drilling operation. The main sump filled and eventually overflowed before drilling had been completed. Shallow catchment ponds were then constructed by scraping up surface soil to form dikes (Plate 5). This corrective measure was only partially successful, however. Total containment of the drilling fluids proved to be impossible because the silty soil, once saturated, made poor dikes. Seepage occurred through the dikes and drilling fluids also escaped via breaches created by slumping.

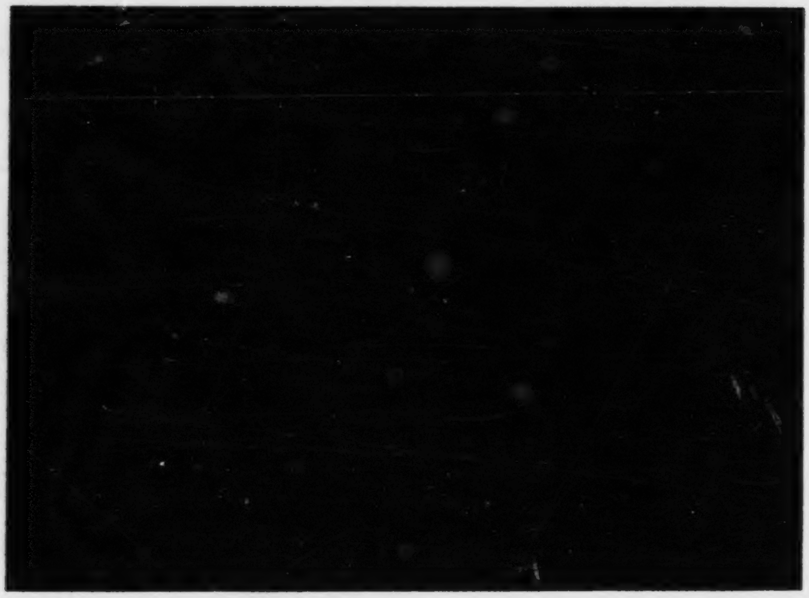
When the site was visited in July 1977, there was no evidence to suggest further deterioration of the sumps. Drilling fluids appeared to be well-contained, although slumping of the sump and the catchment pond infill was noticeable. A thin, surface spill of drilling mud crossed the sample grid and extended 85 m downslope from the dike furthest from the well-head (Plate 5). Presumably, this spill resulted from fluids slopping over the dike during infilling or from leakage through a dike beach.

Plate 5.

Air view of Apollo C-73 showing sump overflow and catchment ponds. Caterpillar on left is diking the third pond.

Surface drilling mud spill at Apollo C-73 (light grey area).

Plate 5 (continued)



Sparse plant growth confined to edges of polygons in an undisturbed area at Apollo C-73.

Table 23. Total quantities of solids and liquids (excluding water) discharged to well sump at Apollo C-73

Product	Description	Quantity
	SOLIDS	KILOGRAMS
Barite	Barium sulphate	92,545
Bentonite	Montmorillonite clay	85,091
	Salt gel	4,591
Kelzan X-C polymer	Xanthan gum	11,227
Peltex	Ferro-chrome lignosulphonate	1,477
Caustic soda	Sodium hydroxide	6,818
	Paraformaldehyde	152
Dowicide B	Sodium trichlorophenate	102
	Sodium chromate	455
	Aluminum stearate	46
	Sodium bicarbonate	591
Soda ash	Sodium carbonate	1,318
C.M.C.	Sodium carboxymethyl cellulose	182
	Chrome alum	773
	Chromic chloride	932
D.P.I.		27
TOTAL		206,327
	LIQUIDS	LITRES
Pipelax		250
TOTAL		250

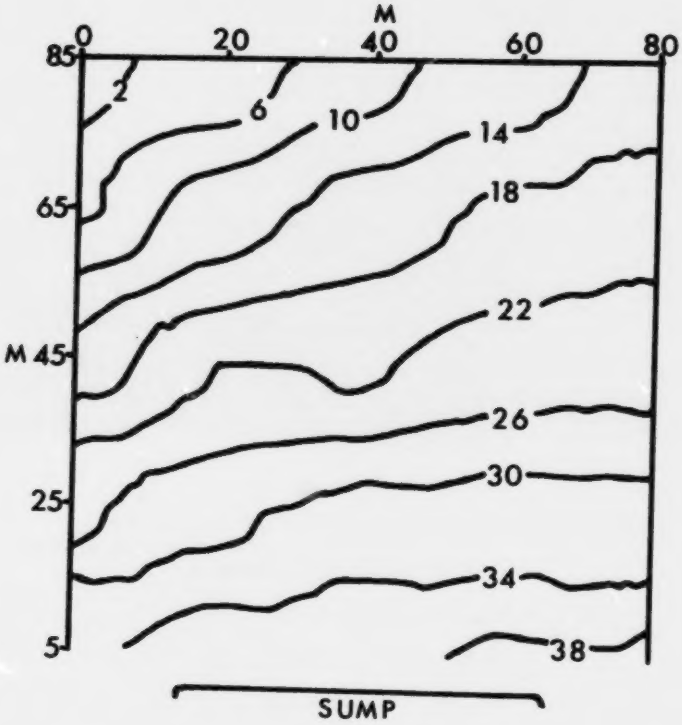

M
0
20
40
60
80
85
65
M 45
25
5
2
6
10
14
18
22
26
30
34
38
SUMP

Figure 36. Topography at Apollo C-73 (contour intervals in dm).

No gully erosion of the sump infill had occurred nor movement of this material downslope by meltwater.

Scarification of the soil surface was extensive at 0-50 m from the catchment dike and vehicle tracks were noticeable in this area. Salt accumulations were small except along borders of the mud spill crossing the sample grid. Vegetation was virtually absent from the heavily scarified zone. In the undisturbed areas, plant cover was almost entirely restricted to cracks on the perimeters of polygons (Plate 5). The slopes below the site (outside the sample grid) support tundra meadow vegetation because of their protected topographic position and seepage benefits. These areas, however, appeared largely unaffected by the drilling operation.

5.5.2 Active layer depth:

Determination of active layer depth at Apollo C-73 was largely impossible due to the high stone content of the soil. The few measurements that were taken indicated a mean depth to the frost-table in mid July of 58.2 ± 2.6 cm. This was greater than at other sites by about 10 cm or more possibly because of the virtual absence of any insulating vegetation.

5.5.3 Soil ion content:

Potassium at Apollo C-73 was distributed evenly throughout the upper 20 cm of the active layer (measurement of the basal 5 cm of the active layer at each sample grid coordinate was not possible hence ion levels at this depth are not reported). The levels of potassium in soil downslope of the sump did not differ significantly from background (Table 24). There was no correlation between soil potassium distribution and distance from the sump.

A trend of decreasing concentrations of extractable sodium with increasing distance downslope from the sump was evident in the surface 5 cm of the active layer (Table 24).

Mean sodium concentrations at this soil depth were approximately 387% of background in the area between 5 m and 65 m from the sump. However, this trend was not significant because of appreciable cross-grid variation in sodium levels (Fig. 37). Elevated sodium concentrations at the soil surface coincided almost exactly with the area of spilled drilling mud. Levels ranging from 920% to 1,620% of background were measured in the centre of this spill at distances of 5-65 m from the sump.

Relatively low sodium levels at 15-20 cm soil depth indicated that movement of this ion down through the active layer was limited (Table 24). Concentrations 5 m from the sump were 374%

Table 24. Mean concentrations (with standard errors) of extractable cations and chloride in soil at Apollo C-73

Soil depth (cm)	Concentration (mg/100 g) at distance from sump (m) 5	25	45	65	85	UD
POTASSIUM						
0 - 5	15.0 ± 1.8	16.2 ± 1.5	12.4 ± 1.0	12.5 ± 0.8	12.3 ± 1.0	14.0 ± 0.5
15 - 20	14.6 ± 1.0	12.3 ± 1.0	15.5 ± 1.8	15.0 ± 1.0	13.2 ± 1.2	15.9 ± 1.9
SODIUM						
0 - 5	10.0 ± 6.4	8.8 ± 3.8	10.1 ± 7.6	9.8 ± 6.0	4.4 ± 1.2	2.5 ± 0.5
15 - 20	7.1 ± 4.4	3.2 ± 1.0	2.1 ± 0.1	4.6 ± 1.3	3.0 ± 1.3	1.9 ± 0.4
BARIUM						
0 - 5	4.1 ± 1.3	4.0 ± 1.0	2.3 ± 0.2	2.4 ± 0.4	4.3 ± 1.3	1.6 ± 0.2
15 - 20	4.1 ± 1.3	2.2 ± 0.5	2.2 ± 0.2	3.1 ± 0.6	2.5 ± 0.2	2.1 ± 0.1
MANGANESE						
0 - 5	0.22 ± 0.09	0.21 ± 0.08	0.15 ± 0.04	0.14 ± 0.03	0.14 ± 0.05	0.17 ± 0.005
15 - 20	0.21 ± 0.10	0.11 ± 0.05	0.12 ± 0.03	0.10 ± 0.03	0.07 ± 0.09	0.10 ± 0.025
CHLORIDE						
0 - 5	88 ± 1	88 ± 1	88 ± 1	87 ± 1	87 ± 1	85 ± 1
15 - 20	86 ± 1	85 ± 1	87 ± 1	86 ± 1	84 ± 1	84 ± 1

UD - undisturbed area

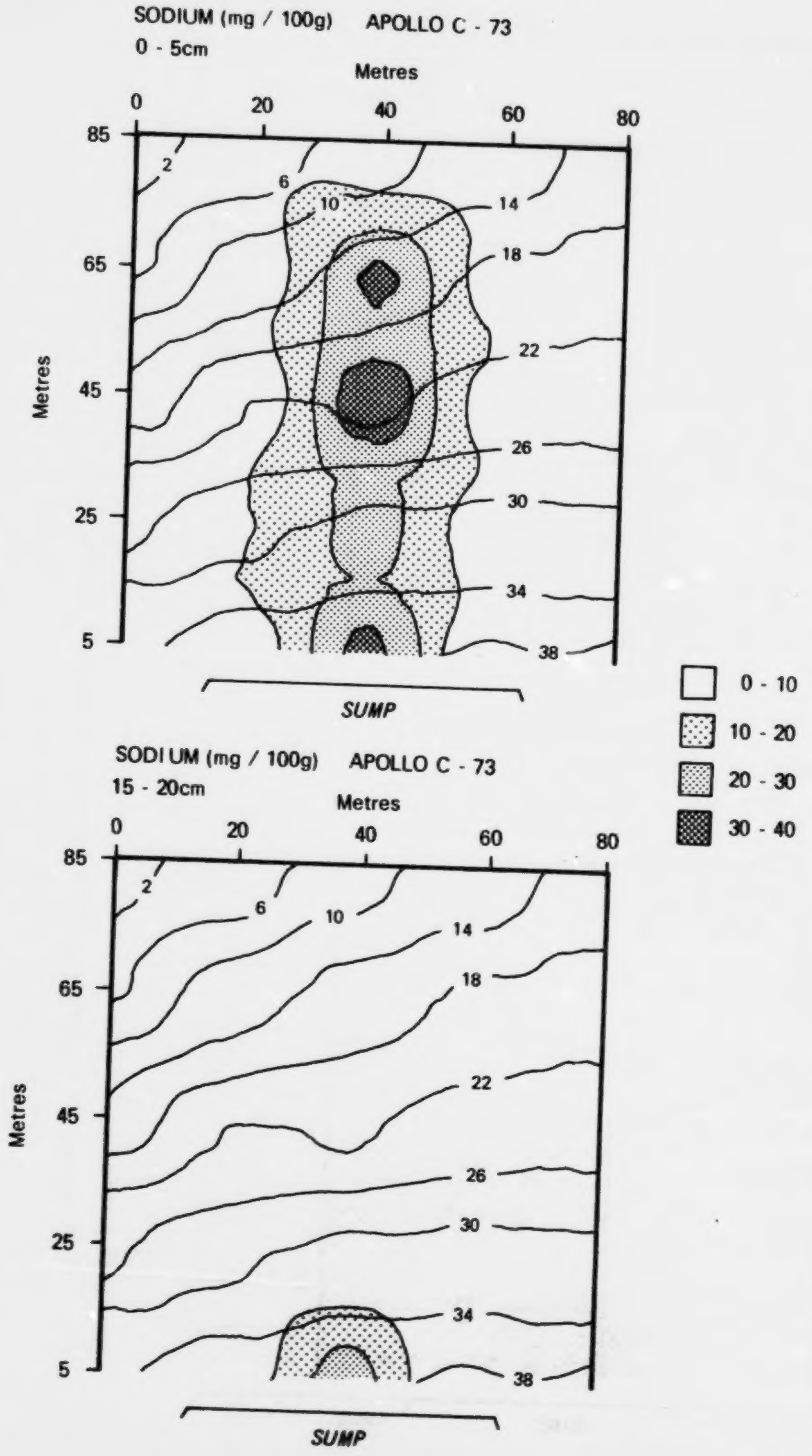

SODIUM (mg / 100g) APOLLO C - 73
0 - 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
2
6
10
14
18
22
26
30
34
38
SUMP
SODIUM (mg / 100g) APOLLO C - 73
15 - 20cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
2
6
10
14
18
22
26
30
34
38
SUMP
0 - 10
10 - 20
20 - 30
30 - 40

Figure 37. Sodium concentrations in soil at Apollo C-73. Contour intervals are in dm.

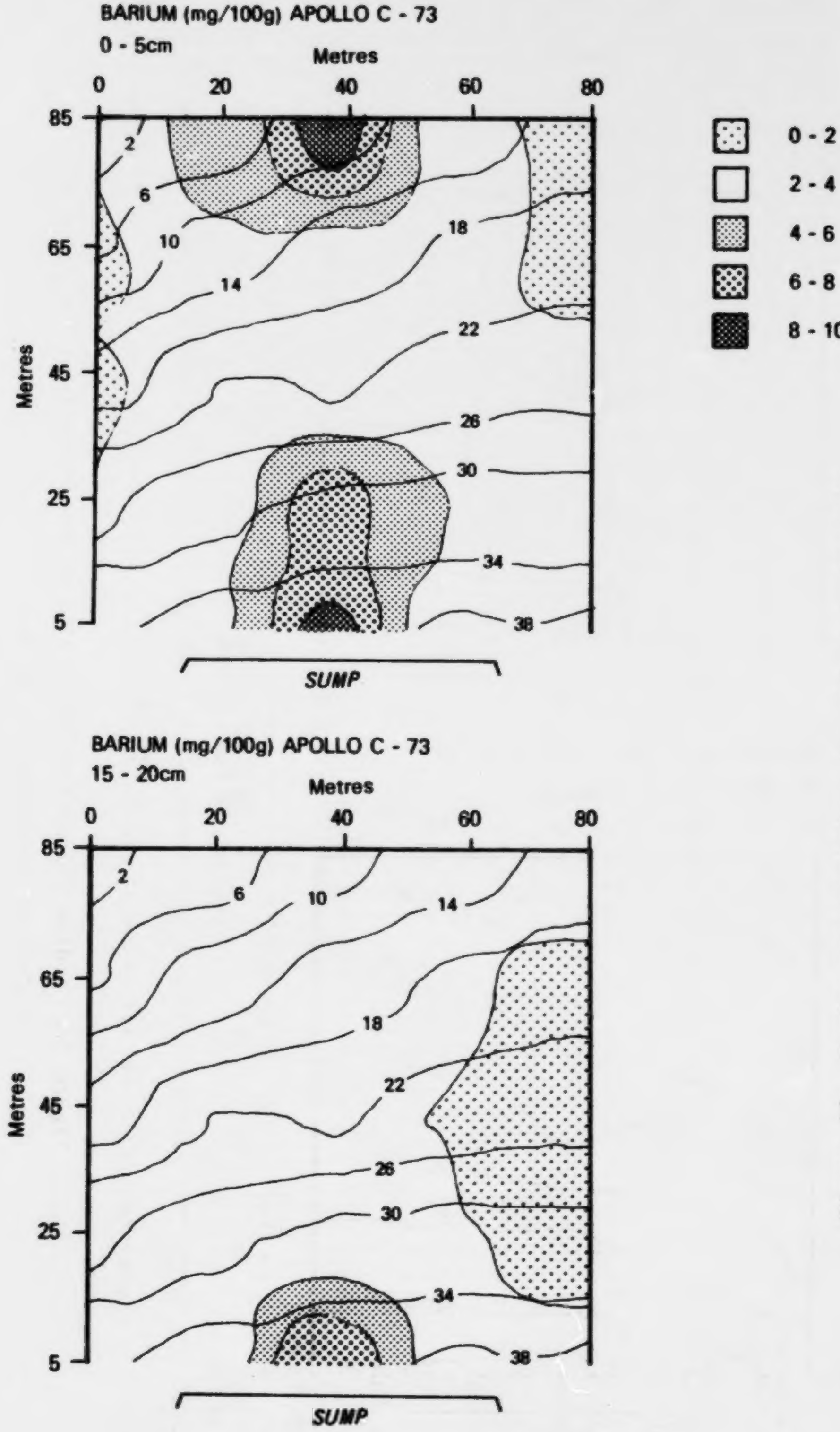
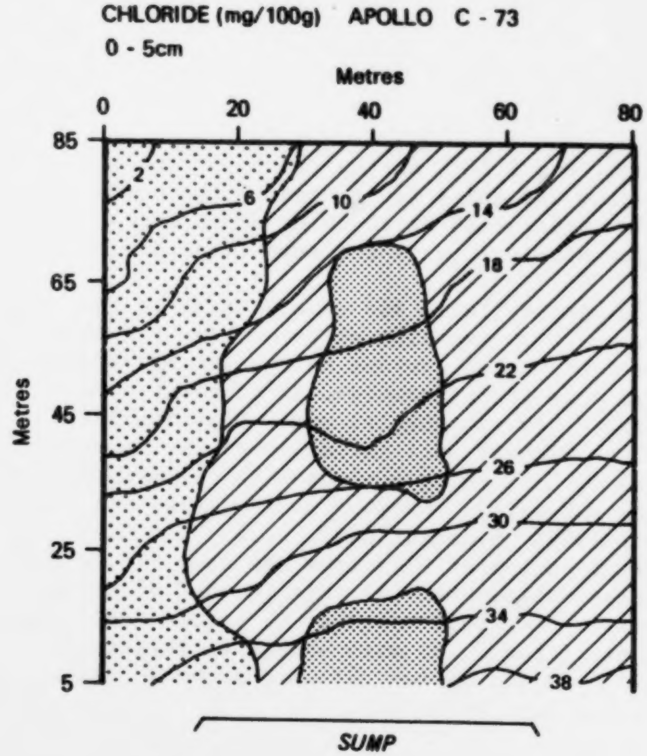

BARIUM (mg/100g) APOLLO C - 73
0 - 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
2
6
10
14
18
22
26
30
34
38
SUMP
BARIUM (mg/100g) APOLLO C - 73
15 - 20cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
2
6
10
14
18
22
26
30
34
38
SUMP
0 - 2
2 - 4
4 - 6
6 - 8
8 - 10

Figure 38. Barium concentrations in soil at Apollo C-73. Contour intervals are in dm.


CHLORIDE (mg/100g) APOLLO C - 73
0 - 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
2
6
10
14
18
22
26
30
34
38
SUMP

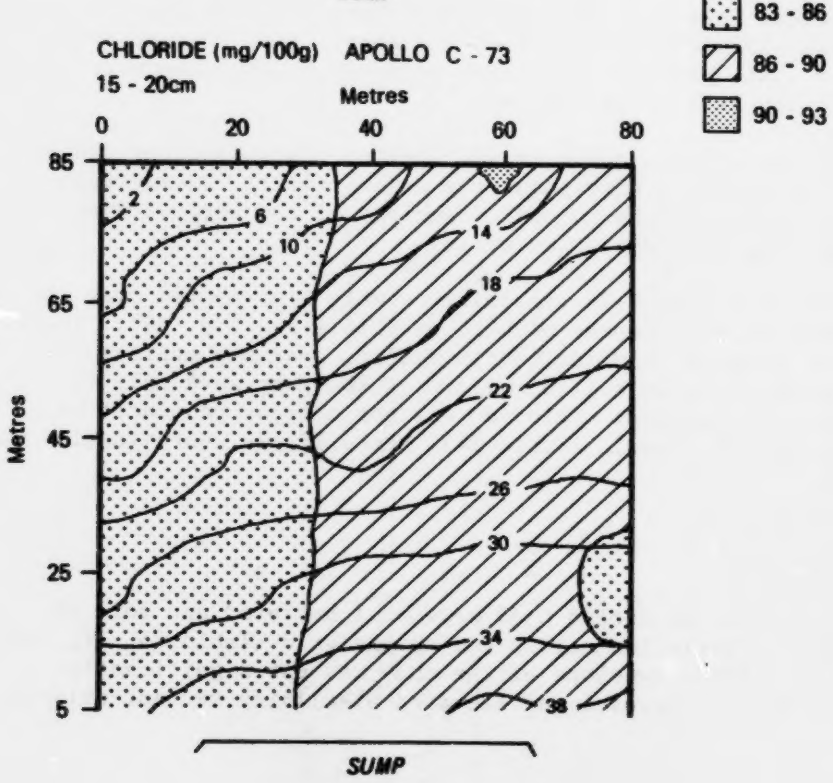

CHLORIDE (mg/100g) APOLLO C - 73
15 - 20cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
2
6
10
14
18
22
26
30
34
38
SUMP
83 - 86
86 - 90
90 - 93

Figure 39. Chloride concentrations in soil at Apollo C-73. Contour intervals are in dm.

of background on average, and 1,289% at the centre of the mud spill. Mobility of sodium was quite restricted in the heavy clay-silt soils and elevated levels at 15-20 cm depth were confined to a small area within 10 m of the sump (Fig. 37).

Levels of extractable barium (Table 24) were greater in the clays at Apollo C-73 than in the sandier soils at Cape Fleetwood L-21 and Charles Point G-07. Mean surface barium concentrations at 5-25 m from the sump were approximately 253% of background levels but this difference was not significant. Distribution maps (Fig. 38) showed the highest soil barium concentrations 5 m from the sump at depths of 0-20 cm coincident with the mid-portion of the surface drilling mud spill. Average barium levels at this point were approximately 489% of background. Relatively high surface concentrations of barium at 85 m from the sump (Table 24) indicated that some downslope movement of this ion had occurred, but this was inconclusive. Vertical movement of barium down through the soil profile was restricted. The main source of barium contamination at Apollo C-73 was barium sulphate added in large quantities to the drilling mud (Table 24).

Extractable levels of soil manganese were very low and there was no evidence of contamination from the sump. Mean concentrations of this ion at 0-20 cm soil depths adjacent to the sump were approximately 159% of background.

Copper, zinc, lead, chromium and cadmium concentrations ranged from 0-0.03 mg/100 g throughout the active layer. Extractable levels of these cations in soil downslope of the sump were no different than in undisturbed areas.

Chloride at Apollo C-73 was fairly evenly distributed over the sample grid at soil depths of 0-20 cm (Table 24, Fig. 39). There was no evidence of chloride contamination. Maximum extractable levels of this ion in soil downslope of the sump were only 4% higher than background. Chloride was not a major component of the drilling mud formula (Table 24), hence little contamination was expected.

5.5.4 Soil pH:

The clay-silts at Apollo C-73 were well buffered and soil pH showed little variation across the sample grid (Table 25, Fig. 40). Soil pH at 0-20 m downslope of the sump was not significantly different from background and elevated alkalinity was not evident.

Table 25. Mean soil pH (with standard errors) at Apollo C-73

Soil depth (cm)	pH at distance from sump (m) 5	25	45	65	85	UD
0 - 5	7.2 ± 0.2	7.4 ± 0.2	7.1 ± 0.3	7.2 ± 0.2	7.3 ± 0.1	7.3 ± 0.5
15 - 20	7.2 ± 0.2	6.9 ± 0.2	7.1 ± 0.2	7.2 ± 0.1	7.1 ± 0.1	7.4 ± 0.4

UD - undisturbed area

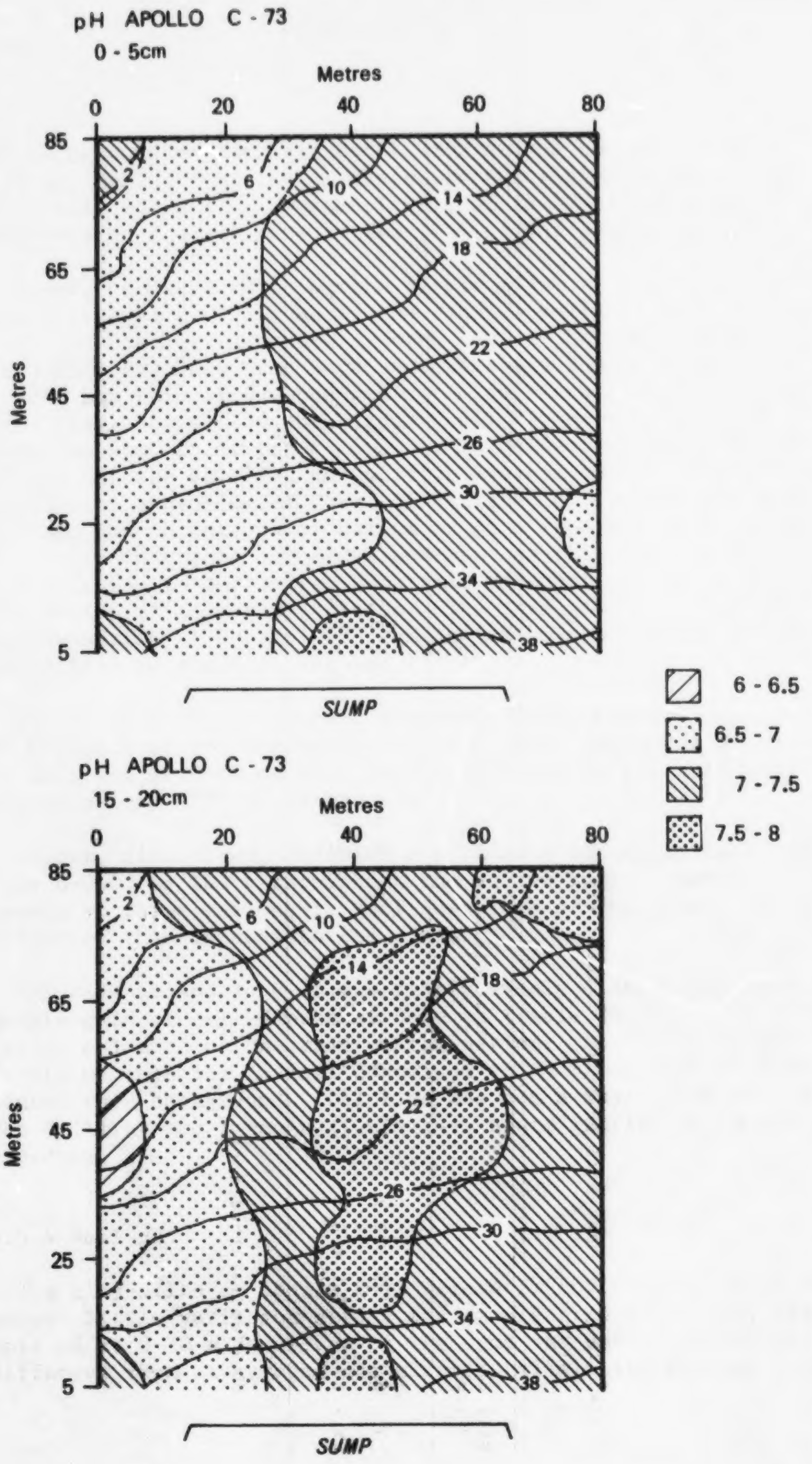

pH APOLLO C - 73
0 - 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
2
6
10
14
18
22
26
30
34
38
SUMP
pH APOLLO C - 73
15 - 20cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
2
6
10
14
18
22
26
30
34
38
SUMP
▨ 6 - 6.5
▨ 6.5 - 7
▨ 7 - 7.5
▨ 7.5 - 8

Figure 40. Soil pH at Apollo C-73.
Contour intervals are in dm.

5.5.5 Vegetation distribution:

Percentage frequencies of plant species at Apollo C-73 are listed in Table 26. Considerably fewer species occurred downslope of the sump compared with undisturbed areas. These reductions in species richness at 5, 25 and 45 m from the berm were 87%, 40% and 70% respectively.

Occurrence of a few species was greatly reduced in the severely disrupted areas within 10 m of the sump (Table 26), the remainder were absent. Species frequency generally increased with distance downslope, but increases for many species were not large. Some of the more disturbance-resistant species which occurred relatively frequently in the disturbed zone 25 m from the sump berm included _Thamnolia subuliformis_, _Alopecurus alpinus_, _Parrya arctica_ R. Br. and _Saxifraga rivularis_ (Table 26). No species increased in occurrence close to the sump, although many were more frequent at downslope distances of 45-65 m than at 85 m. The reduction in species frequency at 85 m downslope was not related to disturbance but reflected a relative lack of plant supporting thermokarst cracks.

Low VDI values between 0-45 m from the sump (Table 26) were indicative of severe vegetation disturbance in this area. VDI values between 45 m and 85 m from the sump were, on average, 25% lower than VDI for the undisturbed area (Table 26). Vegetation disturbance resulting from scarification was a factor 45 m downslope, but at 85 m it was non-existent. Increased plant cover in undisturbed areas outside the sample grid was mainly due to growth in more sheltered microsites.

Axis 1 in the reciprocal averaging ordination accounted for 24% of the variability in species incidence. The second axis extracted 13% of the residual variance. Axes 1 and 2 combined only accounted for 37% of the variability in species incidence data indicating considerable heterogeneity in the distribution of vegetation at Apollo C-73.

The most disturbed CD class IV vegetation was relatively restricted in extent and occurred only within 30 m of the sump (Fig. 41). Scarification by vehicle passage was extensive in this area. Moderately disturbed vegetation (CD class III) was more extensive and occurred up to 80 m downslope from the sump berm (Fig. 41). This distribution pattern was mainly related to vehicle passage. Slightly elevated levels of soil sodium and chloride may also have had some effect. CD class II and I vegetation (least disturbed) was common especially towards the edges of the sample grid.

5.5.6 Ion content of plants:

Concentrations of potassium, sodium and chloride in the dominant species at Apollo C-73 are listed in Table 27.

Table 26. Percentage frequency of plant species at Apollo C-73
(UD -- undisturbed vegetation)

Species	Distance from sump (m)					
	5	25	45	65	85	UD
MOSSES						
Ditrichum flexicaule			10	5	10	75
Pogonatum alpinum var. septentrionale			25	20	15	88
Dead moss	35	50	75	95	100	100
LICHENS						
Cetraria cucullata			30	25	20	50
Cetraria delisei			25	30	15	100
Cetraria tilesii			20	20		25
Parmelia omphalodes		10	50	30	35	75
Pertusaria dactylina	5	15	65	55	45	100
Pseudephebe pubescens			20	20	5	38
Thamnolia subuliformis	10	30	70	60	40	100
Lichen sp.	15	20	70	85	90	50
HIGHER PLANTS						
Alopecurus alpinus		30	30	25	30	50
Cardamine bellidifolia		10	55	25	45	50
Draba alpina		25	75	55	90	63
Draba corymbosa		10	45	65	55	100
Festuca brachyphylla		15	70	45	80	75
Luzula sp.		5	40	10	20	50
Minuartia rossii		15	60	55	65	100
Oxyria digyna		5	45	25	20	50
Papaver radicatum		25	65	85	90	88
Parrya arctica		30	50	40	55	75
Potentilla hyparctica			5			
Ranunculus sulphureus						13
Salix arctica					5	13
Saxifraga caespitosa			20	15	20	63
Saxifraga flagellaris ssp. platysepala		10	35	20	20	75
Saxifraga foliolosa			5		5	
Saxifraga nivalis		5	20	10	15	75
Saxifraga oppositifolia		10	10	5	25	50
Saxifraga rivularis		30	45	55	70	75
Stellaria monantha			20			
VDI	4	11	37	32	35	60

VDI - vegetation disturbance index (%)

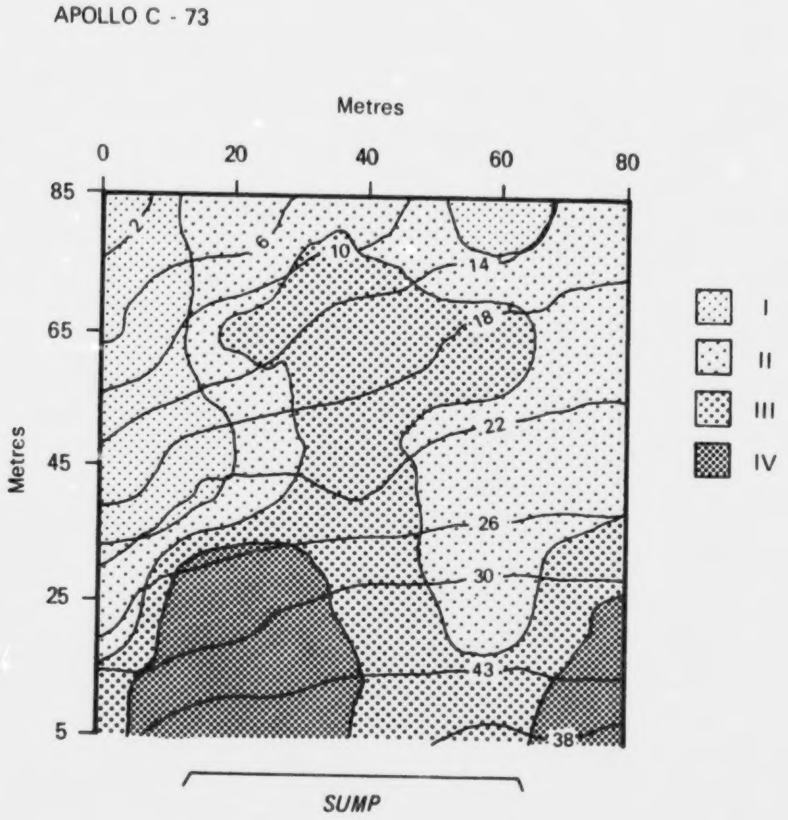

APOLLO C - 73
Metres
0
20
40
60
80
85
65
45
25
5
Metres
2
6
10
14
18
22
26
30
43
38
I
II
III
IV
SUMP

Figure 41. Community disturbance (CD) class map of Apollo C-73.

Contour intervals are in dm and vegetation ranges from least disturbed (Class I) to most disturbed (Class IV).

Table 27. Concentrations (mg/100 g) of total potassium, sodium and chloride in plant species at Apollo C-73 (UD -- undisturbed area)

Species	Distance from sump (m)					
	5	25	45	65	85	UD
POTASSIUM						
Alopecurus alpinus		75.6	69.3	105.3	74.7	67.5
Oxyria digyna		91.8	97.2		62.1	72.9
Parrya arctica		105.5	102.6	128.7	120.8	89.1
SODIUM						
Alopecurus alpinus		46.5	73.0	113.3	64.3	33.0
Oxyria digyna		150.0	187.5		47.0	45.5
Parrya arctica		43.6	46.8	79.2	54.8	44.0
CHLORIDE						
Alopecurus alpinus		2,107.4	3,140.8	3,244.8	2,596.2	1,934.6
Oxyria digyna		1,561.1	1,995.9		1,321.3	903.2
Parrya arctica		2,784.8	2,673.3	4,049.5	3,153.2	1,616.8

All three dominants growing in soils contaminated by a surface drilling mud spill between 45 m and 85 m from the sump showed elevated tissue concentrations of chloride. Chloride levels in *Parrya arctica* 65 m from the sump were 250% of background (Table 27).

Oxyria digyna concentrated sodium in its tissues between 25 m and 45 m from the sump. Sodium levels in *Oxyria* at these points averaged 371% of background (Table 27). Tissue concentrations of sodium in *Alopecurus alpinus* were high in areas of drilling mud contamination. Levels of the cation in this species at 65 m downslope were 342% of background (Table 27). Elevated sodium concentrations in *Parrya arctica* only occurred between 65 m and 85 m from the sump.

Tissue levels of potassium did not differ greatly from background in any of the dominants sampled. There was some tendency for greater accumulations of this ion by plants growing in contaminated soils close to the sump (Table 27) but this was inconclusive.

5.6 Chads Creek B-64

5.6.1 Site description and well history:

Chads Creek B-64 (76° 23' 08.20"N 109° 54' 21.00"W) is located on an upland of Christopher shale, above the marine limit on the Sabine Peninsula of Melville Island (Fig. 1b). Regionally the landform is an undulating plain. The well is situated on an area of low relief (10-15 m) in a valley lightly dissected by a dendritic drainage network. Soils are dominated by clays and silts and contain ground ice in moderate amounts. Subsurface soil moisture is high. The vegetation type is a wet tundra meadow.

B-64 is a capped gas well drilled to a final depth of 5,021 m. The well was spudded on December 6, 1974 and completed on June 27, 1975. A Bentonite-Kelzan X-C polymer mud system lightly treated with lignosulphonate was employed in the drilling. Mud weights were up to 1.38 kg/l. Amounts of mud solids, liquid additives (excluding water) and washing agents are listed in Table 28. Total quantity of mud solids (1,116,240 kg) was very high compared to amounts used at other shallower exploratory wells in the High Arctic. Freshwater only was used in the drilling operation.

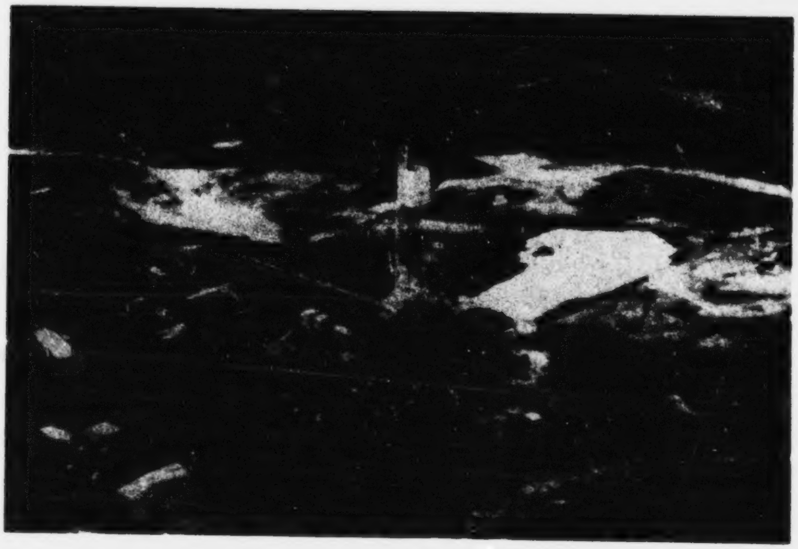
Waste fluids were originally discharged to a sump approximately 46 m x 46 m x 4 m excavated in very poorly drained fine silt and clay. The sump was located on slightly sloping terrain (1°-2°) uphill from the rig site. Sump infill was heavy clay.

Severe sump problems developed at Chads Creek B-64 during the drilling and infilling operations.

A 3,659 m deep well was originally planned, and a sump believed sufficient in size to contain the drilling fluids constructed in December 1974. At the end of drilling in June 1975, however, the well was over 4,878 m deep. Problems encountered down the hole extended the drilling period.

By February 1975, the original sump was within 0.3 m of overflowing, and in March the sump overflowed (Plate 6). In late May, two new sumps were constructed. But by June 1975 these two new sumps were also full and began to spill drilling wastes onto the tundra. The spilled fluids drained downslope into the rig camp resulting in erosion and waterlogging of the site (Plate 6). This in turn aggravated disruption of the lease by scarification and rutting due to heavy vehicle operation when the active layer was thawed.

Plate 6.



Air view of Chads Creek B-64 showing sump overflow and waterlogged, heavily scarified terrain across the lease.

Gully between sumps at Chads Creek B-64 showing heavily scarified area and salt encrusted spillage of drilling mud (light grey area).

Table 28. Total quantities of solids and liquids (excluding water) discharged to well sump at Chads Creek B-64

Product	Description	Quantity
	SOLIDS	KILOGRAMS
Barite	Barium sulphate	941,980
Bentonite	Montmorillonite clay	97,545
Kelzan X-C polymer	Xanthan gum	10,841
Visbestos	Asbestos	5,432
Peltex	Ferro-chrome lignosulphonate	18,477
	Lignite	3,386
Caustic soda	Sodium hydroxide	13,727
Lime	Calcium hydroxide	2,182
	Sawdust	4,432
Kwik-seal	Wood fiber and cellophane	6,291
	Mica	4,409
	Walnut shells	2,432
Celloflakes		500
Dowicide B	Sodium trichlorophenate	45
	Calcium chloride	364
	Sodium bicarbonate	3,091
S.A.P.P.	Sodium acid pyrophosphate	470
	Sodium carbonate	636
TOTAL		1,116,240
	LIQUIDS	LITRES
	Diesel fuel	5,668
LD-7		364
LD-8		45
Pipelax		119
TOTAL		6,196

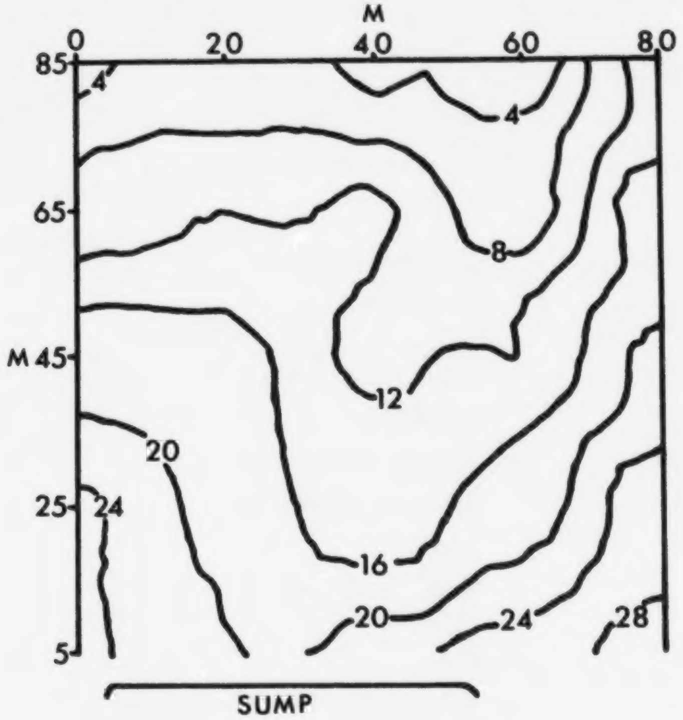

M
0
20
40
60
80
85
65
M 45
25
5
4
4
8
12
16
20
20
24
24
28
SUMP

Figure 42. Topography at Chads Creek B-64 (contour intervals in dm).

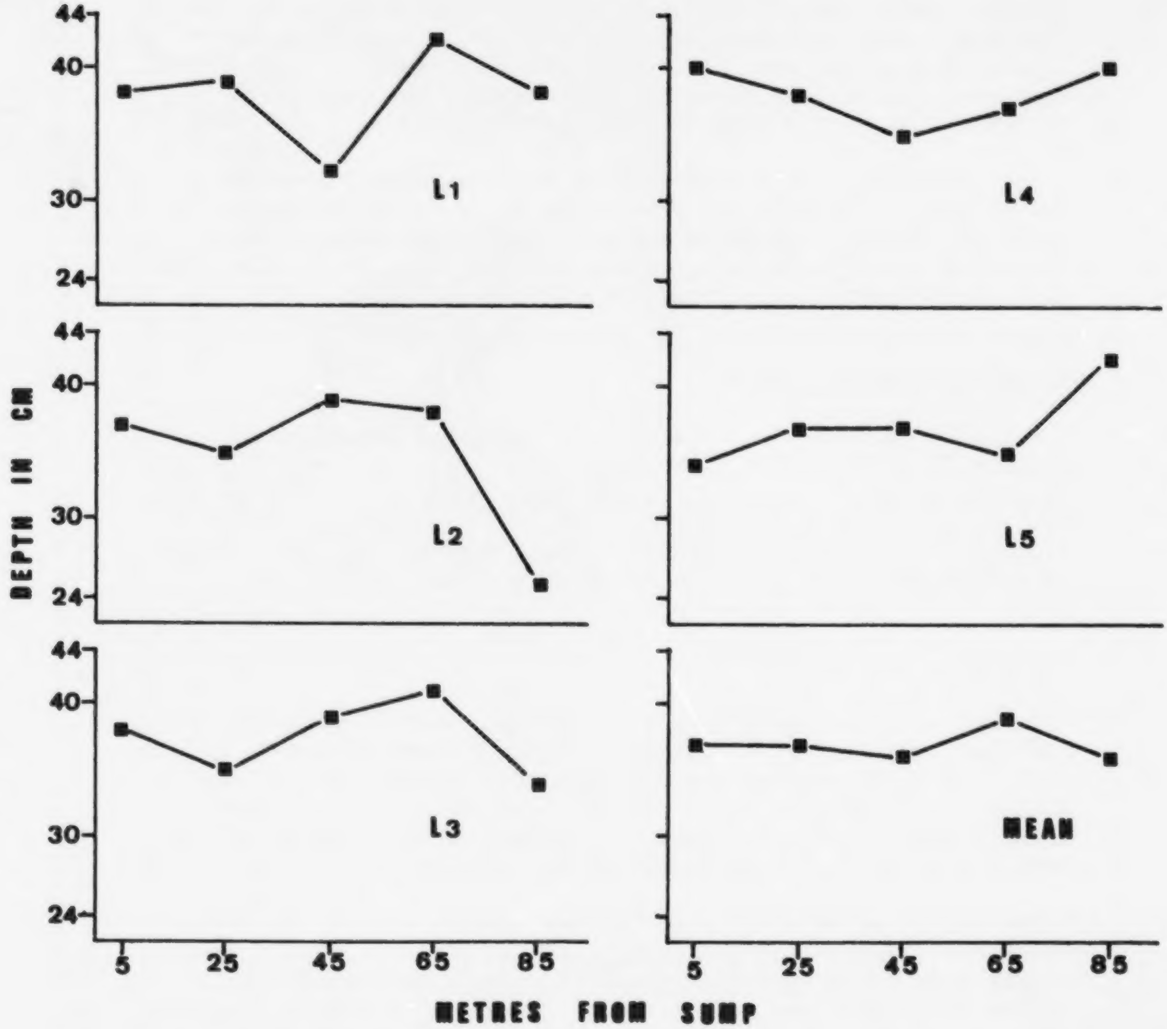


Figure 43. Active layer depth at Chads Creek B-64 (measured on July 26, 1977).

These problems were accentuated when the sumps were infilled in the winter of 1975-76. Sump fluids were not adequately frozen at that time and, as a consequence, were squeezed to the surface and became mixed with the overburden.

Extensive slumping of infill material was evident over the sump areas in July 1977, but drilling fluids appeared to be contained. Gully erosion had occurred and a wide channel crossed the sample grid (Plate 6, Fig. 42) located between two sumps. Spills of pink and grey drilling muds were common throughout the sump area, especially along gullies and near the well-head. Salt accumulations at the soil surface were widespread.

Scarification of the soil surface was extensive across the sample grid. The original vegetation had been destroyed in the immediate vicinity of sumps and very little revegetation was occurring. Alopecurus alpinus was the main recolonizing species. This species was also dominant in undisturbed areas.

5.6.2 Active layer depth:

Depth to the frost-table was highly variable downslope of the sump at Chads Creek B-64. The average active layer depth in late July was about 37 cm but it ranged from 25 cm to 42 cm (Fig. 43). Shallowest depths occurred at the base of a large gully 85 m from the sump created by fluid spillage during drilling. Permafrost conditions at the site now appear to have stabilized.

5.6.3 Soil ion content:

Extractable potassium levels at all soil depths downslope of the main sump did not differ significantly from background (Table 29). There was some evidence of elevated levels 5 m from the sump at 15-20 cm soil depth (ca. 121% of background). However, these trends were inconclusive. Potassium containing compounds were not major constituents of the drilling mud formula (Table 29).

Contamination of soil by sodium was clearly evident at Chads Creek B-64. Extractable sodium levels at all soil depths were higher than background throughout the sample grid (Table 29). Sodium concentrations were greatest between 45 m and 65 m downslope from the main sump. Mean values at soil depths of 0-5 cm, 15-20 cm and immediately above the frost-table were 365%, 267% and 298% of background respectively. Distribution maps of soil sodium (Fig. 44) show the accumulations in this area to originate from a source other than the main sump. This spillage was probably from one of the subsidiary sumps constructed in May 1976. Accumulations of sodium at some points on the spillage were up to 1,000% of background.

Table 29. Mean concentrations (with standard errors) of extractable cations and chloride in soil at Chads Creek B-64

Soil depth (cm)	Concentration (mg/100 g) at distance from sump (m) 5	25	45	65	85	UD
POTASSIUM						
0 - 5	40.1 ± 1.8	37.7 ± 3.3	37.9 ± 2.1	39.6 ± 5.7	34.4 ± 2.5	36.1 ± 3.2
15 - 20	41.5 ± 2.4	43.2 ± 5.3	43.0 ± 7.6	36.5 ± 4.9	38.7 ± 3.2	35.1 ± 1.7
P + 5	42.3 ± 1.7	42.9 ± 1.3	41.9 ± 2.1	43.6 ± 1.5	43.7 ± 4.8	44.1 ± 0.7
SODIUM						
0 - 5	32.7 ± 11.9	49.8 ± 12.3	80.2 ± 25.9	61.3 ± 33.9	34.8 ± 15.5	19.4 ± 8.1
15 - 20	17.8 ± 2.4	19.5 ± 3.1	44.0 ± 24.6	43.0 ± 19.3	19.8 ± 5.9	16.3 ± 1.0
P + 5	21.9 ± 8.0	44.6 ± 30.0	60.9 ± 28.9	51.7 ± 29.0	20.9 ± 7.6	18.9 ± 5.4
BARIUM						
0 - 5	5.2 ± 0.2	6.8 ± 1.2	4.1 ± 1.3	4.0 ± 1.1	4.3 ± 0.8	2.8 ± 0.2
15 - 20	3.3 ± 0.2	3.7 ± 0.4	3.2 ± 0.5	2.8 ± 0.5	3.5 ± 0.5	3.5 ± 0.1
P + 5	2.7 ± 0.3	3.2 ± 0.8	3.6 ± 0.5	3.3 ± 0.4	3.1 ± 0.3	3.6 ± 0.02
MANGANESE						
0 - 5	0.25 ± 0.02	0.40 ± 0.10	0.64 ± 0.30	0.22 ± 0.07	0.40 ± 0.20	0.19 ± 0.03
15 - 20	0.26 ± 0.10	0.18 ± 0.04	0.18 ± 0.06	0.13 ± 0.01	0.38 ± 0.22	0.16 ± 0.02
P + 5	1.14 ± 0.70	0.31 ± 0.11	0.27 ± 0.16	0.25 ± 0.15	0.47 ± 0.31	0.12 ± 0.03
LEAD						
0 - 5	0.07 ± 0.01	0.13 ± 0.03	0.10 ± 0.03	0.09 ± 0.02	0.04 ± 0.01	0.08 ± 0.04
15 - 20	0.05 ± 0.02	0.08 ± 0.04	0.11 ± 0.02	0.09 ± 0.02	0.05 ± 0.03	0.12 ± 0.02
P + 5	0.09 ± 0.03	0.11 ± 0.05	0.07 ± 0.01	0.10 ± 0.03	0.05 ± 0.02	0.07
CHLORIDE						
0 - 5	110 ± 18	98 ± 4	99 ± 4	96 ± 3	94 ± 3	89 ± 1
15 - 20	93 ± 2	94 ± 1	92 ± 1	91 ± 1	92 ± 1	90 ± 1
P + 5	92 ± 1	92 ± 1	92 ± 1	92 ± 2	90 ± 1	88 ± 2

UD - undisturbed area

P - frost-table

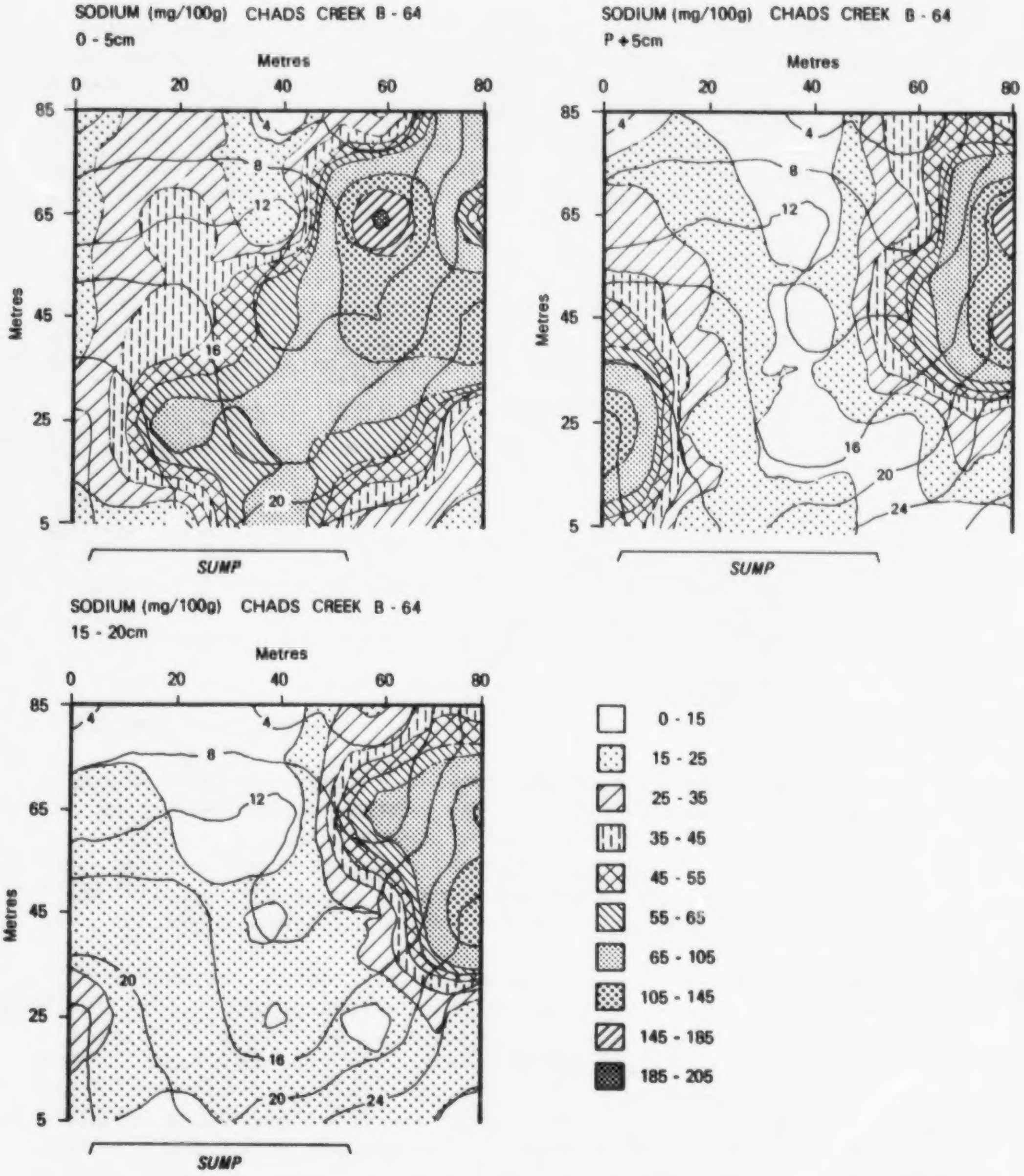

SODIUM (mg/100g) CHADS CREEK B - 64
0 - 5cm
SODIUM (mg/100g) CHADS CREEK B - 64
P + 5cm
SODIUM (mg/100g) CHADS CREEK B - 64
15 - 20cm
Metres
0
20
40
60
80
85
65
45
25
5
4
8
12
16
20
24
SUMP
0 - 15
15 - 25
25 - 35
35 - 45
45 - 55
55 - 65
65 - 105
105 - 145
145 - 185
185 - 205

Figure 44. Sodium concentrations in soil at Chads Creek B-64.

Contour intervals are in dm and P+5 cm
-- 5 cm above the frost-table.

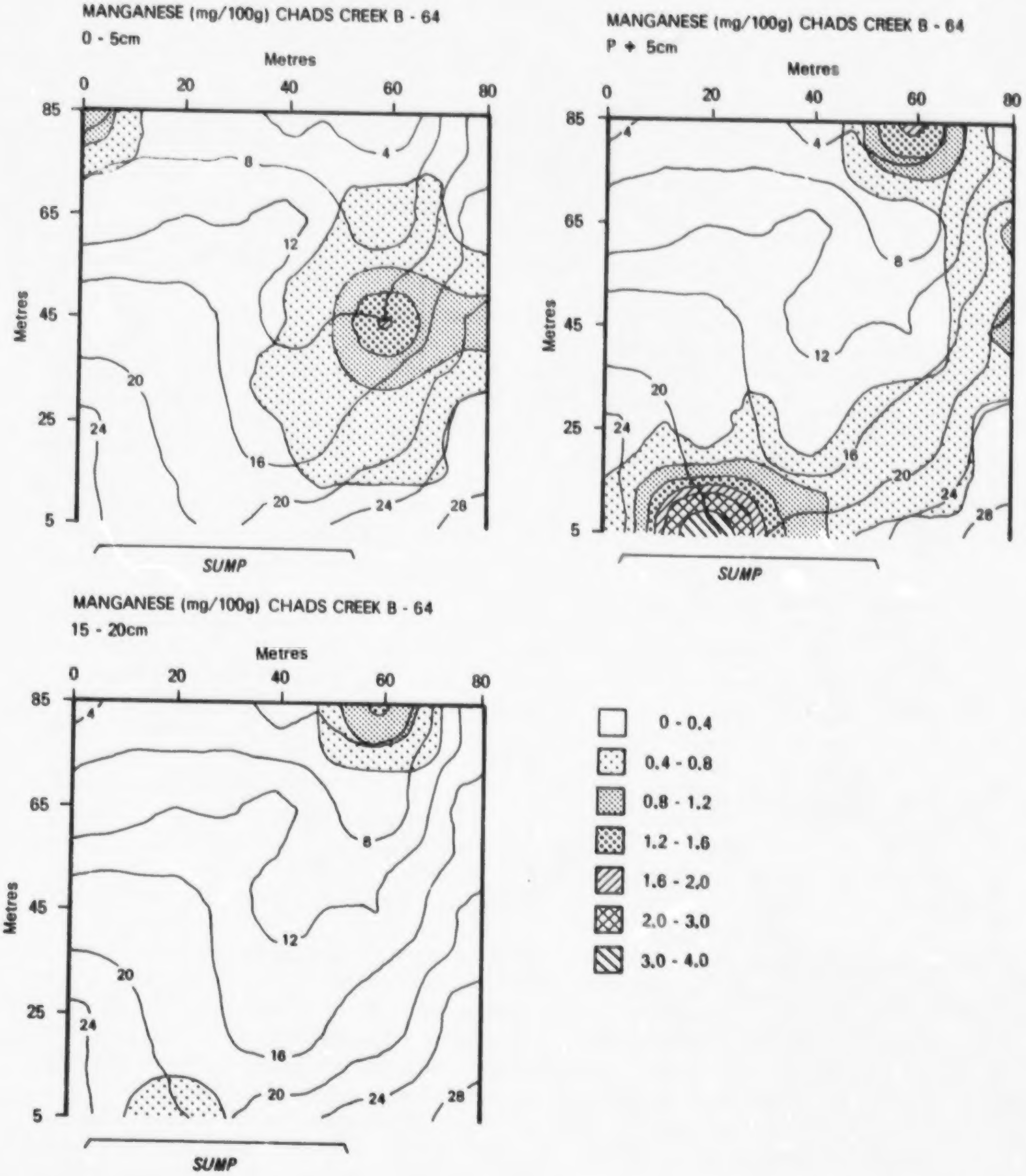
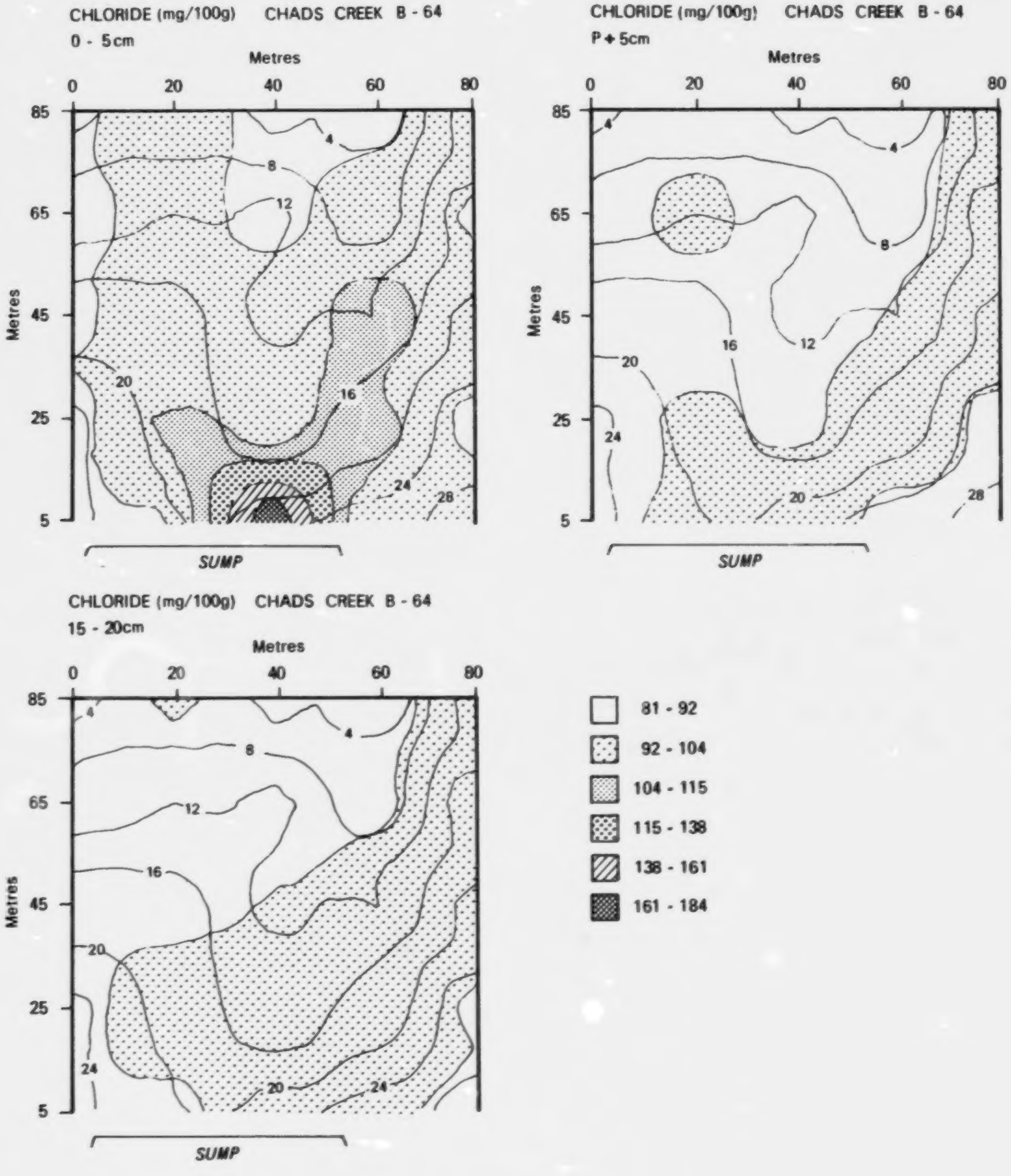

MANGANESE (mg/100g) CHADS CREEK B - 64
0 - 5cm
MANGANESE (mg/100g) CHADS CREEK B - 64
P + 5cm
MANGANESE (mg/100g) CHADS CREEK B - 64
15 - 20cm
Metres
0
20
40
60
80
85
65
45
25
5
4
8
12
16
20
24
28
SUMP
☐ 0 - 0.4
0.4 - 0.8
0.8 - 1.2
1.2 - 1.6
▨ 1.6 - 2.0
2.0 - 3.0
3.0 - 4.0

Figure 45. Manganese concentrations in soil at Chads Creek B-64.
Contour intervals are in dm and P+5 cm
-- 5 cm above the frost table.



CHLORIDE (mg/100g) CHADS CREEK B - 64
0 - 5cm

CHLORIDE (mg/100g) CHADS CREEK B - 64
P + 5cm

CHLORIDE (mg/100g) CHADS CREEK B - 64
15 - 20cm

Metres
0
20
40
60
80
85
65
45
25
5
Metres
4
8
12
16
20
24
28
SUMP
81 - 92
92 - 104
104 - 115
115 - 138
138 - 161
161 - 184

Figure 46. Chloride concentrations in soil at Chads Creek B-64.

Contour intervals are in dm and P+5 cm
-- 5 cm above the frost-table.

Elevated exchangeable soil sodium levels also occurred in the area adjacent to the main sump (Fig. 44). Mean concentration of this cation 5 m from the berm at the soil surface was 169% of background, but at some points was 297% greater than background levels.

Drilling mud spilled onto the soil surface was very rich in extractable sodium (ca. 3,371% of background). Downward leaching of sodium from the mud accounted for concentrations up to 1,767% of background at 5-15 cm depth. Sodium containing compounds were a major component of the drilling fluids used at Chads Creek B-64 (Table 29), hence high levels of this cation in soil and spilled mud were expected.

Surface barium concentrations up to 240% greater than background at grid coordinates close to the main and secondary sumps were indicative of some soil contamination by this ion. Extractable barium levels at other soil depths showed little correlation with proximity to the sump and were close to background levels (Table 29). Mobility of barium in the heavy clays was restricted as indicated by the relatively low values even in areas of obvious mud spillage. Presumably, the large amount of barium added to the drilling mud (Table 29) was bound to the bentonite clay and soil particles, and exists in unavailable form.

Manganese concentrations varied widely at all soil depths downslope of the main sump (Table 29). Levels of soil manganese throughout the sample grid were low but were generally higher than background. Elevated concentrations appeared to be associated with leakage of fluids from the main and subsidiary sumps (Fig. 45). Manganese levels immediately adjacent to the main sump at the base of the active layer were up to 3,250% of background in some places. High concentrations (ca. 868% of background) occurred at the soil surface close to the subsidiary sump (45 m downslope from the main sump). Manganese levels in spilled drilling mud were 184% of background.

Mean extractable lead levels in soil across the sample grid were not significantly different from background (Table 29). However, relatively high accumulations of lead were measured in some areas. For example, leakage of lead-containing drilling fluids from the main sump was indicated by extractable levels averaging 293% of background throughout the active layer at one sample point 25 m from the berm. Levels of extractable lead in spilled drilling mud (3,875% of background) were high. Lead concentrations in soil (5-15 cm depth) immediately below this mud spill were 1,550% of background.

Concentrations of zinc, chromium and copper were very low throughout the active layer over the entire sample grid (0-0.08 mg/100 g). No widespread contamination of soil by these heavy metals was evident. Relatively high accumulations occurred locally in areas of drilling mud spillage. Levels of zinc, chromium and copper in spilled muds were 2,850%, 1,400% and 400% of background respectively.

Extractable soil chloride levels downslope of the sumps at Chads Creek B-64 were generally slightly greater than background (Table 29), but appreciable accumulations only occurred at the soil surface immediately adjacent to the main sump (Fig. 46). Concentrations in this area were up to 204% of background at some points. Chloride containing compounds were not added to the mud system in any great quantities (Table 29) and this was reflected by low levels (ca. 111% of background) in spilled drilling mud.

5.6.4 Soil pH:

The heavy clay soils at Chads Creek B-64 were well-buffered and there was little variation in pH downslope of the sump (Table 30). pH was generally acidic and build up of alkalinity was slight even in areas where spillage of drilling fluids had occurred. The trend of slightly higher pH throughout the active layer 25 m downslope of the main sump (Table 30) was not significant. However, some correlation between elevated pH levels and proximity to both main and secondary sumps was evident in the maps of soil pH (Fig. 47), especially in the basal 5 cm of the active layer.

5.6.5 Surface water ion content:

Standing water was measured in pools on the surface of the sump infill and at varying distances downslope from the berm. Levels of soluble ions in surface pools upslope from the well lease were taken as background.

Concentrations of cadmium, chromium, zinc, copper, lead and manganese ranging from 0-0.04 mg/l were not significant. Levels of these ions in standing water proximal to the sump were no different from background.

Significant contamination of surface pools by potassium, sodium and chloride was evident with high concentrations of these ions occurring close to the sump and diminishing downslope (Table 31).

Table 30. Mean soil pH (with standard errors) at Chads Creek B-64

Soil depth (cm)	pH at distance from sump (m)				
	5	25	45	65	85	UD
0 - 5	5.9 ± 0.1	6.6 ± 0.4	5.9 ± 0.2	5.9 ± 0.2	5.8 ± 0.09	5.6 ± 0.05
15 - 20	5.7 ± 0.2	6.0 ± 0.2	5.9 ± 0.09	5.9 ± 0.01	5.5 ± 0.2	5.9 ± 0.05
P + 5	5.5 ± 0.5	5.9 ± 0.3	6.4 ± 0.1	5.9 ± 0.4	5.6 ± 0.4	6.0 ± 0.11

UD - undisturbed area P - frost-table

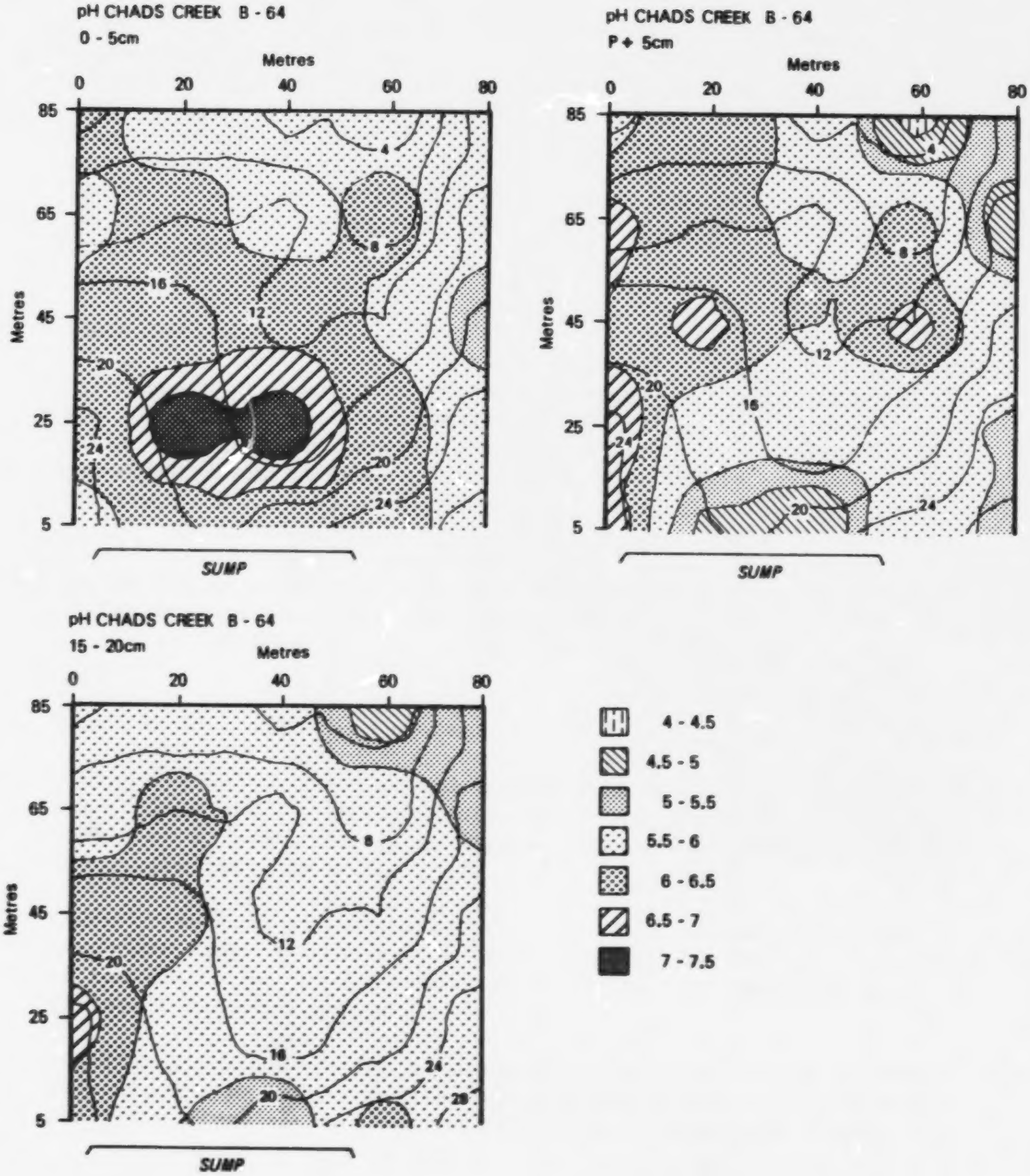

pH CHADS CREEK B - 64
0 - 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
4
8
12
16
20
20
24
24
SUMP
pH CHADS CREEK B - 64
P+ 5cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
4
8
12
16
20
20
24
24
SUMP
pH CHADS CREEK B - 64
15 - 20cm
Metres
0
20
40
60
80
85
65
45
25
5
Metres
8
12
16
20
20
24
28
SUMP
4 - 4.5
4.5 - 5
5 - 5.5
5.5 - 6
6 - 6.5
6.5 - 7
7 - 7.5

Figure 47. Soil pH at Chads Creek B-64.

Contour intervals are in dm and P+5 cm
-- 5 cm above the frost-table.

Table 31. Ion content of standing water at Chads Creek B-64

Distance from the sump (m)	Ion concentration (mg/1)		
	K	Na	Cl
200 upslope	5.9	21.0	16.7
on sump infill	11.3	360.0	1,137.3
1 downslope	18.6	1,073.3	3,311.7
30 downslope	8.9	89.0	327.8
80 downslope	7.3	73.0	66.9
200 downslope	8.6	123.7	100.4

Levels of potassium in pools on the sump infill and 1 m downslope were 192% and 315% of background respectively. At distances of 30 m to 200 m from the berm, surface water potassium content approached background more closely (Table 31). Sodium concentration in standing water on the sump infill was 1,714% of background and 511% of background in an area of spilled drilling mud 1 m from the berm. Levels of this ion were high even at distances of 200 m downslope from the sump (ca. 589% of background). Contamination by chloride was very evident in disturbed areas with surface water concentrations 6,800% and 19,800% of background on the sump infill and 1 m from the berm respectively. Levels of this ion in pools diminished downslope of the lease, but at 200 m from the sump, chloride was still 600% of background.

5.6.6 Vegetation distribution:

Species richness downslope of the sump at Chads Creek B-64 was greatly reduced compared to undisturbed areas. The greatest reductions, at 45 m and 65 m from the sump, were 79% and 68% respectively (Table 32).

Widespread destruction of vegetation in sump areas was indicated by very low species frequencies at 5-65 m downslope. Occurrence of most species increased 85 m from the main sump, but even at this distance percentage frequency values were generally much lower than in the undisturbed area. Destruction of vegetation at distances of 45 m to 85 m from the main sump resulted from disturbance associated with the secondary sump at Chads Creek.

The more disturbance-resistant species included Ditrichum flexicaule, Alopecurus alpinus and Saxifraga rivularis. Compared

Table 32. Percentage frequency of plant species at Chads Creek B-64 (UD -- undisturbed vegetation)

Species	Distance from sump (m)					
	5	25	45	65	85	UD
MOSSES						
Aulacomnium turgidum	15				5	100
Ditrichum flexicaule	20	25		15	35	100
Pogonatum alpinum var. septentrionale		15			30	100
Dead moss	60	60	60	40	80	100
LICHENS						
Cetraria delisei						38
Parmelia omphalodes		5				100
Pertusaria dactylina	15	10		5	10	100
Thamnolia subuliformis						25
HIGHER PLANTS						
Alopecurus alpinus	85	50	45	65	85	100
Cerastium regelii	5					50
Draba alpina	5	10			15	100
Draba corymbosa					15	88
Festuca brachyphylla						38
Luzula sp.		15		10	40	50
Papaver radicatum	5	5			35	100
Potentilla hyparctica						13
Ranunculus sulphureus	5	20	5	5	30	100
Saxifraga nivalis						38
Saxifraga rivularis	10	10	20	5	50	100
Stellaria monantha			5		5	50
VDI	11	11	7	7	22	75

VDI - vegetation disturbance index (%)

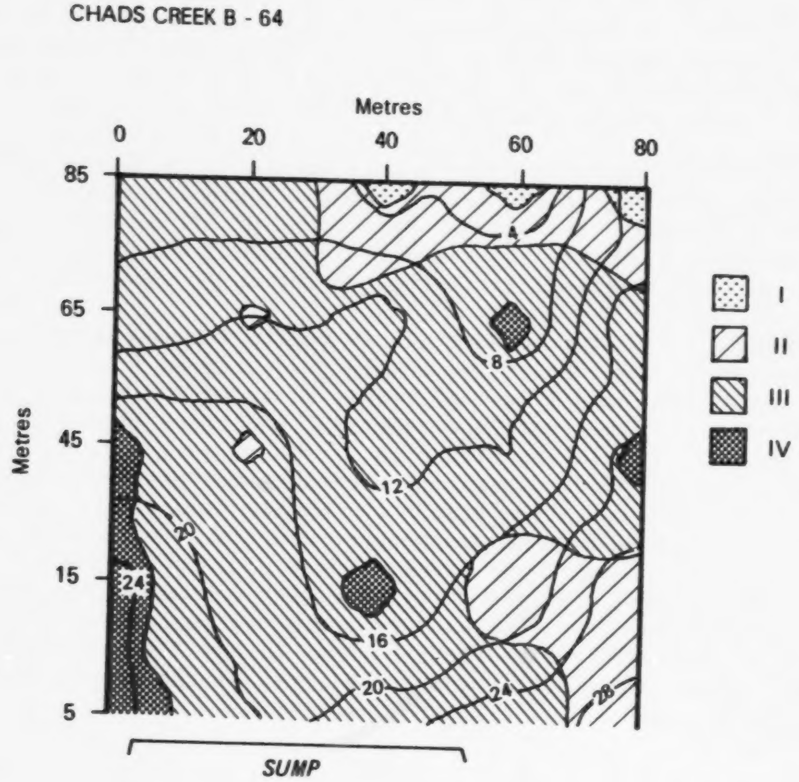

CHADS CREEK B - 64
Metres
0
20
40
60
80
85
65
45
15
5
Metres
4
8
12
20
24
16
20
24
28
SUMP
I
II
III
IV

Figure 48. Community disturbance (CD) class map of Chads Creek B-64.

Contour intervals are in dm and vegetation ranges from least disturbed (Class I) to most disturbed (Class IV).

to the other species recorded, these elements of the vegetation (especially Alopecurus alpinus) occurred with relatively high frequency throughout the sample grid (Table 32). Occurrence of all species close to the sumps was less than in undisturbed areas.

VDI values were very low downslope compared to the value for the undisturbed area (Table 32) reflecting the effects of disturbance on both species richness and frequency. Lowest VDI values were at 45 m and 65 m from the main sump in an area of severe disruption associated with the secondary sump. Effects of this disruption extended 85 m downslope as shown by the 53% lower VDI value compared to VDI for the undisturbed area (Table 32). Plant cover in the undisturbed areas was mainly confined to shallow depressions separating small earth hummocks. This micropattern was totally destroyed in areas close to the sumps.

Axis 1 in the reciprocal average ordination accounted for 32% of the variation in species incidence. Axis 2 accounted for 24% of the residual variance. A high total of 57% of the variability in species incidence was extracted by axes 1 and 2 indicative of the general homeogeneity in the vegetation at Chads Creek B-64.

The highly disturbed CD class IV vegetation was largely confined to the edge of the sample grid between 5 m and 45 m from the main sump (Fig. 48). This distribution mainly reflected the effects of mechanical disruption, but there also appeared to be some correlation with high levels of soil sodium, manganese and chloride. Wide distribution of intermediately disturbed CD class III vegetation across the sample grid testified to the high level of mechanical disturbance associated with sump construction and reclamation at Chads Creek. Occurrence of CD class III vegetation also appeared correlated with contamination by soil sodium leached from the main and secondary sumps (cf. Figs. 44 and 48). Slightly disturbed CD class II and I vegetation was confined to small areas at the periphery of the sample grid (Fig. 48).

5.6.7 Ion content of plants:

Levels of potassium, sodium and chloride in Alopecurus alpinus and Papaver radicatum at Chads Creek B-64 showed no correlation with contamination of soil by salt. Concentrations of these ions in plants throughout the sample grid did not differ appreciably from background (Table 33) and there were no gradients of change in tissue levels with proximity to sumps. Presumably, salts released from spilt drilling fluids were mainly bound to exchange sites on the clay soils in forms largely unavailable to plants.

Table 33. Concentrations (mg/100 g) of total potassium, sodium and chloride in plant species at Chads Creek B-64
(UD -- undisturbed area)

Species	Distance from sump (m)					
	5	25	45	65	85	UD
POTASSIUM						
Alopecurus alpinus	139.4	136.4	138.6	149.4	141.1	140.4
Papaver radicatum	137.7	156.6		156.6		156.6
SODIUM						
Alopecurus alpinus	109.4	100.5	142.5	171.9	119.0	82.7
Papaver radicatum	58.3	64.5		96.0		60.5
CHLORIDE						
Alopecurus alpinus	2,566.4	1,923.5	2,454.2	2,213.4	2,310.9	2,051.7
Papaver radicatum	1,817.5	1,934.6		1,990.4		2,068.4

6 DISCUSSION

6.1 Causes of drilling fluid spillage and chemical contamination:

Severe breakdown of sumps leading to massive leakage of drilling fluids had not occurred at any of the six wellsites visited. French (1978b) noted that drilling fluids in High Arctic sumps quickly freeze *in situ*. Our observations support this conclusion.

Major fluid spills in the High Arctic occur mainly during the drilling and sump rehabilitation operations. Unfrozen fluid can be spilt into the tundra due to careless handling of the mud processing equipment. A mud spill near the wellhead at Robert Harbour K-07 developed in this manner. Spillage can also occur when sumps overflow or are infilled before the sump fluids are frozen. Problems of this nature occurred both at Apollo C-73 and Chads Creek B-64. Spilled bags of drilling chemicals are a further source of potentially toxic contaminants. This type of spillage was noted near the sumps at Roberts Harbour K-07 and Chads Creek B-64.

Subsidence of poorly consolidated sump infill had occurred at all six wellsites. This was a result of the thermal processes described briefly in section 1.2, and in more detail by French (1978a, 1978b). Such slumping of reclaimed sumps may expose frozen drilling fluids to thaw and subsequent erosion. The problem is worsened when headward erosion of gullies cuts into the sump fill and buried mud. Mud spills via these processes occurred at Robert Harbour K-07 and a potential danger of them developing exists at Cape Fleetwood L-21.

Contamination of soils by drilling chemicals may arise when frozen fluids become mixed with fill during sump reclamation. When the fill melts at the surface during the spring and summer, these chemicals are released to the environment. Spillage via this process accounted for the elevated levels of some ions in soil at Bent Horn N-72 and Charles Point G-07. Drilling chemicals may also be dispersed by erosion of contaminated fill, as at Cape Fleetwood L-21.

At all six wellsites, drilling sumps were "perched" on high topographic positions and at some sites; e.g. Cape Fleetwood L-21, they were located on slopes. A consequence was that spilled drilling fluids and sump infill were distributed widely by snowmelt. Contamination of soil and vegetation by drilling wastes could have been restricted in extent by locating sumps on areas of low relief, preferably in shallow natural depressions.

6.2 Soil contamination by drilling fluid:

Ammonium acetate extractable cations reflect the exchange capacity of the soil and are a measure of the ions available to plants. Analyses of acetate extracts of soil indicated contamination by a number of cations, originating in drilling fluids or sump infill. The main pollutants were sodium, potassium and barium. Zinc, lead, chromium, copper and manganese were minor contaminants at some sites. Levels of other heavy metals, such as cadmium, were negligable. Water soluble chloride was also a contaminant at all six wellsites.

Soil contamination by potassium and sodium occurred in association with spillage of chloride-rich drilling fluids. Pollution of soil by these ions was especially marked at Bent Horn N-72 and Robert Harbour K-07. Potassium was present in direct association with chloride as KCl in drilling fluids. Sodium compounds were also common constituents of mud recipes.

Potassium levels in contaminated soil downslope of sumps were low relative to the large amounts of KCl added to the mud systems. Fixation of potassium in unavailable form by preferential attachment to exchange sites on the bentonite (Page and Baver 1939) coupled with containment of the bulk of the frozen drilling muds in the sumps accounted for this result.

Sodium was released to the environment in appreciable quantities. In uncontaminated High Arctic soils the predominant cation on the exchange complex is calcium, whereas sodium is one of the least important. After contact with sodium-rich drilling fluids the proportion of sodium on the soil exchange sites increases sharply relative to calcium and magnesium (Edwards and Blauel 1975). This was reflected by significant increases in extractable sodium throughout drilling fluid contaminated areas.

Soils containing exchangeable sodium in the order of 3-10 m.e./100 g are termed solenetzic (Biosystems 1974). Levels of extractable sodium at this concentration or more occurred at five wellsites, the exception was Apollo C-73. Some deterioration of structure may have resulted from dispersion of particles in these "sodic" soils. In soils with a high clay component, such as at Chads Creek B-64, sodium-induced dispersion restricts drainage and the soil becomes deflocculated and compact instead of being friable (Edwards and Blauel 1975).

Potassium, sodium and chloride percolated down through the active layer at all six wellsites. At some locations, the highest concentrations of these ions were found at the thaw interface. This was due to migration of ion-rich water to the cold regions of the soil profile where it is trapped by the largely impermeable permafrost.

At other locations, high concentrations of potassium, sodium and chloride at the soil surface resulted from rapid evaporation of ion-rich water. This process was especially evident in sump fill and spilled drilling mud where evaporation had led to the formation of a salt crust.

Distribution of soluble cations in the soil was a product of a number of dynamic physical processes. In most High Arctic soils a strong temperature gradient exists during the growing season in association with a corresponding moisture gradient from dry at the surface (temperature 5-10°C) to wet and cold (0 to -3° C) at the thaw interface (Babb and Bliss 1974). Because wet soil conducts heat more readily than dry, once a moisture gradient is established in the spring, it is further enhanced by subsequent changes in the thermal regime. Any available water (plus ions) tends to move toward the colder zone in the soil profile (Taylor 1965), while evaporation acts to dry the surface. Many soils on arid-appearing sites can thus approach saturation at the 10-20 cm depth. This condition was observed at most of the wellsites and was especially noticeable at Apollo C-73.

Although the highest concentrations of potassium, sodium and chloride were generally found in soil within 30 m of sumps, some downgrade movement of these ions had occurred at Cape Fleetwood L-21, Bent Horn N-72, Charles Point G-07 and Robert Harbour K-07. Migration was most rapid near the surface (0-5 cm) due to surface run-off. Rate of ion movement downslope is dependent on the solubility of compounds released from drilling fluids; the amount of surface run-off; ground-water movements through the contaminated areas; and, soil composition. Potassium, sodium and chloride were all more mobile at the sites with sandy soils than in the silts and clays at Apollo C-73 and Chads Creek B-64. Chloride was the most mobile ion measured at all of the sites.

Mobile ions tend to migrate from upslope areas over time and as they move downgrade the concentrations in higher areas declines. Heavy contamination in areas of elevated topography will therefore be a temporary phenomenon. More permanent contamination may result from further drilling fluid release, or from ponding of ion-rich groundwater in frost-table depressions (this seemed to have happened at Bent Horn N-72).

Zinc contamination of soil was strongly evident at Charles Point G-07. Occurrence of zinc at the base of the active layer indicated downward percolation with groundwater, but concentrations were highest at 0-5 cm depth, especially close to the sump. Downgrade movement of zinc had occurred at all soil depths; however, it was greatest at the surface due to run-off. Some zinc contamination was also noted at Robert Harbour K-07, particularly in drilling mud deposits on the soil surface. Mobility of zinc at this site was restricted and the ion appeared to be mainly bound up on exchange sites in the mud complex.

Lead contamination occurred at Robert Harbour K-07 and Chads Creek B-64, but extractable levels in the soil were generally low. The highest concentrations of lead were measured in the surface 20 cm of soil at both sites. Relative immobility of lead in soils was indicated by its restriction to areas immediately adjacent to sumps. High lead levels in drilling mud at Robert Harbour K-07 suggested that this ion may be an important contaminant in some mud systems. However, because of its low mobility, it probably does not represent a critical pollution danger to the High Arctic environment.

Evidence of copper contamination of soil was only found at Charles Point G-07. Extractable copper occurred in trace amounts, except at 45 m downslope from the sump where relatively high levels occurred within a small area. Copper release from drilling fluids was suspected; however, this could not be proved conclusively.

Limited lateral and downgrade movement suggested that copper mobility was slight even in the sandy soils at Charles Point. Elevated concentrations at the base of the active layer were, however, indicative of downward percolation. Controlling factors for copper availability are pH, soil organic content, proportions of sand and clay, and the presence of other elements such as molybdenum, zinc and aluminium with which copper can react.

Reported ranges for total barium in soils are 100-3,000 ppm with a mean of about 500 ppm (Biosystems 1977b). Approximately 30 ppm occurs as exchangeable barium. Extractable barium at the six wellsites was generally lower than these reported values by a factor of 10 or more. Some barium contamination was evident nonetheless, especially in surface soils at Cape Fleetwood L-21, Robert Harbour K-07, Apollo C-73 and Chads Creek B-64. Relatively high levels at Apollo C-73 were associated with surface deposits of drilling mud.

Little evidence of downgrade or lateral movement through soils indicated that barium mobility was very restricted at all sites. Most of the barium in soils remains in unavailable complex form bonded to mineral material or organic matter. Fixation of barium within drilling mud, which remained largely contained in the sumps, explains why this ion was not a significant soil contaminant even though large amounts of barium-containing weighting agents were added to the mud systems at some sites, e.g. Chads Creek B-64.

Manganese contamination from drilling fluid spillage was evident at Robert Harbour K-07 and Chads Creek B-64. Extractable levels of this ion were low (0.8-4.0 mg/100 g), however, even in the contaminated areas. Extensive downgrade and lateral movement indicated that manganese is sufficiently mobile to allow considerable redistribution. Elevated concentrations throughout the active layer in contaminated areas were also indicative of thorough downward percolation.

Soil acidity was the most important factor controlling manganese availability. High levels at Chads Creek B-64 occurred in areas where pH was low (4.5-5.0). At Bent Horn N-72 concentrations of extractable soil manganese were also strongly correlated with low pH. Relatively high levels were noted at the base of the active layer at some points where conditions were anaerobic and soil pH ranged from 4.0 to 4.5.

Manganese can form complexes with organic matter, occur as an exchangeable ion, or occur in numerous inorganic precipitates. Our results suggest that soil organic content was a big factor controlling manganese distribution. At Charles Point G-07, elevated manganese levels in soil only occurred in areas where soil organic matter content was relatively high. Moreover, manganese concentrations in the organic soils at Bent Horn N-72 were generally higher than in any of the mineral soils at other wellsites.

6.3 Effects of drilling fluid on vegetation:

The highest level of chemical contaminants in soil were generally found on the infilled sumps or close to them where vegetation disturbance from vehicle movement or overburden burial was also most severe. High levels of soil ions were also found in downslope gullies where vegetation was subject to erosion processes. Bent Horn N-72 was the only site where levels of ions in soil, notably potassium, sodium and chloride, were high at a downslope location otherwise unaffected by drilling activities. CD class mapping indicated that vegetation growing in this chemically-enriched soil was disturbed to some extent. However, results of this study do not conclusively prove whether drilling fluid chemicals released to the environment have an effect on High Arctic vegetation.

Plant damage, such as leaf discoloration, leaf shedding and shoot die-back, attributable to high levels of sodium and chloride could not be distinguished from the effects of mechanical disturbance at any of the wellsites. On this basis, it was difficult to determine whether salt levels in the soil were toxic to the High Arctic vegetation. Based on data for spruce and birch in Alberta (Edwards and Blauel 1975), prolonged exposure to chloride levels above 1,500 mg/100 g can result in plant damage. Chloride concentrations of this magnitude and higher occurred at every wellsite except for Apollo C-73 and may have been damaging to the vegetation. Chloride was probably the most toxic to plants out of those extractable soil ions tested. Sodium may have had an indirect effect on vegetation by altering soil structure.

Some High Arctic plant species, including *Alopecurus alpinus*, *Oxyria digyna*, *Luzula* spp., *Parrya arctica* and *Saxifraga oppositifolia*, appeared tolerant of saline conditions. All of these species had the ability to concentrate sodium, potassium and chloride in their tissues and all were found growing in saline soils close to sumps.

True salt tolerance is the genuine ability of the plant cells to withstand high accumulative levels of sodium and chloride ions (Edwards and Blauel 1975). Alopecurus alpinus, in particular, demonstrated this capacity. Tissue concentrations of chloride were very high close to the sumps at Cape Fleetwood L-21, Bent Horn N-72, and Charles Point G-07. Yet, despite these high levels (in the range indicated by Edwards and Blauel 1975 injurious to southerly tree species), individual specimens of Alopecurus seemed healthy with no obvious signs of necrosis. Some of the other salt tolerant species showed reduced performance in contaminated areas.

Plants can also avoid salt stress in the environment by passive salt exclusion, active salt extrusion, and dilution of entering salt. Such species are found growing on salt-rich soils yet do not contain excessively high accumulations of chloride or other highly soluble salts such as potassium and sodium in their tissues. Some of the High Arctic species growing in contaminated soils which fell into this category included Papaver radicatum and Aulacomnium turgidum.

Vegetation responses to levels of chloride, potassium and sodium are complex. Treshow (1970) stated the harmful effect of saline soils is primarily in reducing the rate at which plants absorb water. The excessive concentration of mineral ions increases the osmotic pressure to a degree where a tension is created in the soil solution against which the plant cannot absorb water and as a consequence suffers water stress. Levitt (1970), on the other hand, indicated that primary induced salt stress is the result of ion toxicity and that osmotic and nutritional stress factors are secondary.

Salt stress is known to produce several functional changes in plants prior to injury, such as alterations in respiration, photosynthetic activity, protein synthesis, nucleotide synthesis and enzyme activity. Some of the variables influencing these functional changes and injury responses are listed below:

1) Climatic
    - toxicity increases with light (Strogonov 1964).
    - toxicity increases with temperature (Kaho 1962) (low temperatures in the High Arctic would tend to reduce salt toxicity).

2) Edaphic
    - calcium reduces sodium injury (LaHaye and Epstein 1969) (High Arctic soils are generally rich in calcium thus sodium toxicity to vegetation may be reduced as a consequence).

- ground and surface water dilutes salt concentrations (spring meltwaters may benefit vegetation by diluting high concentrations of salts in the soil and moving them out of the rooting zone and down through the active layer; alternatively, melt-waters may increase salt contamination by continuously flushing salt-laden materials from sumps).
- natural soil salinity (soils in many High Arctic locations are naturally saline due to entrapment of soluble ions in the relatively shallow active layer coupled with rapid evaporation at the surface; undisturbed vegetation can be expected to show some salt tolerance as a consequence).

3) Genetic
- differences in species resistance to salinity (Strogonov 1964) (a species such as *Alopecurus alpinus* capable of growth in highly contaminated soils would likely be more resistant to salt than many of the lichens, for example, which were never found in these contaminated areas).
- differences in salinity resistance among a variety of individuals of the same species (Kadmon 1963, Dewey 1960).

Most of the High Arctic species analyzed exhibited a degree of tolerance to heavy metal contamination. *Alopecurus alpinus*, *Luzula* spp., *Ditrichum flexicaule*, *Papaver radicatum* and *Saxifraga oppositifolia* all concentrated heavy metals in their tissues. However, gradients of heavy metal accumulation with respect to distance from sources of drilling fluid contamination were poorly defined.

Phytotoxic levels of zinc ranging from 40 mg/100 g upwards have been reported by McIlveen *et al* (1975). Extractable zinc levels, even at the contaminated sites, were below this figure. Presumably, zinc concentrations in the soil were not sufficient to cause mortality of High Arctic vegetation, although they may have reduced plant productivity. Zinc is closely enough related to manganese to replace it physically in essential enzymes, but not closely enough related to replace it chemically (Treshow 1970). Zinc may reduce plant productivity by blocking enzyme activity and causing a shortage of manganese.

Relatively high zinc accumulations in some species growing in disturbed and contaminated soils close to sumps occurred at Charles Point G-07 and Cape Fleetwood L-21. At these sites, gradients of zinc accumulations were best defined in *Ditrichum flexicaule*, *Luzula* spp. and *Saxifraga oppositifolia*.

Lead availability to plants is generally less than 1 ppm, but high levels in soil can result in accumulation by vegetation. Near smelters, concentrations ranging from 342 ppm in pine to 175 ppm in yellow birch have been reported (Biosystems 1977a).

However, lead concentrations as low as 2 ppm have been found to inhibit photosynthesis (Bazzaz *et al* 1974). Soil lead levels in the drilling fluid contaminated areas were below these concentrations and probably had little effect on the vegetation. Gradients of lead accumulation in plants were observed at Charles Point G-07 and Robert Harbour K-07, especially in *Luzula* spp., *Saxifraga oppositifolia* and *Papaver radicatum*, but tissue concentrations (0-0.2 ppm) were low.

Available levels of copper in contaminated soil close to sumps were very low at all six wellsites and probably had no effect on vegetation. Plant tissue concentrations of copper were negligable.

Chromium accumulation by plants only occurred at Cape Fleetwood L-21 where it was particularly pronounced in *Alopecurus alpinus*, *Ditrichum flexicaule* and *Papaver radicatum*. High levels of chromium in these species at 85 m from the sump occurred due to concentration of drilling chemicals in a natural gully. Healthy growth of plants with relatively high tissue levels of chromium indicated that the ion was occurring in concentrations below the phytotoxic limit and probably in the non-toxic trivalent form.

Toxic effects of manganese were not observed in drilling fluid contaminated areas. Danger of manganese toxicity to vegetation is reduced with increasing alkalinity. Above pH 6.0. low amounts of the ion may become limiting to plants as manganese is oxidized. Soil pH above 6.0 was common at a number of the wellsites, especially in areas where spillage of base-rich drilling fluids had occurred. These otherwise contaminated soils may well be manganese deficient.

The highest levels of available manganese occurred at Bent Horn N-72 where soil pH was low (below 5.5). Release of manganese from drilling fluids and subsequent uptake by plants was indicated by tissue levels ranging from 30-180 mg/100 g in contaminated areas compared to a background range of 5-20 mg/100 g at this site. The absence of any deleterious effects on vegetation, however, suggested that these concentrations were well below the phytotoxic limit. *Aulacommium turgidum* (Wahlenb.) Schwaegr., *Ditrichum flexicaule*, *Alopecurus alpinus* and *Sphagnum* spp. all concentrated manganese in their tissues.

Levels of heavy metals were obviously below phytotoxic limits in the species sampled; however, whether they were below these limits for all of the vegetation is open to speculation. The levels of zinc and lead in High Arctic species at the six wellsites were below concentrations of these ions reported in vegetation growing on natural mineralization sites in the Low Arctic (Jones *et al* 1976).

Plants can resist heavy metal contamination in a variety of ways. Jones et al (1976) suggested that Low Arctic species such as Empetrum nigrum L. and Cassiope tetragona (L.) D. Don., absorb heavy metals up to a certain point below the toxicity limit after which they do not absorb further quantities due to homeostatic control. Epstein (1972) on the other hand proposed that heavy metal tolerant plants, such as Ledum palustre L., synthesize chelating compounds that form chemical complexes with the metal ions thereby rendering them harmless. There are probably a number of such compounds, each more or less specific for a certain toxic metal (Jones et al 1976).

6.4 Vehicle damage to soil and vegetation:

Tracked vehicle passage was most disruptive to soil in areas close to sumps. The main effects were compaction and ripping of the surface 10 cm. Similar effects have been reported by Babb and Bliss (1974). Blading during sump backfilling was responsible for removal of surface soil at some sites. This problem was especially noticeable at Bent Horn N-72 where the organic mat on the soil surface was totally removed in places.

Compaction or removal of part of the active layer slightly reduces its insulative capacity and sub-surface ice-rich materials may then melt, releasing moisture upwards. This results in higher thermal conductivity at the surface and in further acceleration of thaw (Babb and Bliss 1974). Such soil changes following heavy vehicle movement were probably responsible for deepening of the active layer 45 m downslope of the sump at Bent Horn N-72, within 20 m of the sumps at Charles Point G-07 and Robert Harbour K-07, and close to the secondary sump at Chads Creek B-64.

Ruts of varying depth were noted in high traffic areas at some sites, e.g. Bent Horn N-72, Robert Harbour K-07 and Chads Creek B-64. Sites on soils with a high organic matter and ice content, such as Bent Horn N-72, or on clay-silts, such as Chads Creek B-64, were especially prone to rutting. Soil disturbance at the latter was greatly increased by vehicle movement across the tundra at times when the active layer was unfrozen.

Passage of heavy tracked vehicles was particularly damaging to High Arctic plants. Metal cleats on the 'caterpillar' tracks had crushed the vegetation and ripped plants out of the soil at all six wellsites. Plants were also uprooted during blading operations such as sump infilling and snow clearing. The damage caused by the blade itself is magnified by the abrasive action of soil or fill pushed across the surface.

Lichens, such as *Pseudephebe pubescens* (L.) Choisy and *Cetraria tilesii* Ach. amongst others, and mosses, such as *Aulacomnium turgidum* and *Plagiomnium medium* var. *septentrionale* (Lindb.) Kop., are very sensitive to crushing and were greatly reduced in high traffic areas. Sensitive higher plants included most of the *Saxifraga* species and *Potentilla hyparctica* Malte. Their sensitivity may have been a consequence of exposed aerial parts. Plants growing from basal meristems, such as *Luzula* spp. and *Alopecurus alpinus*, were protected from crushing and were commonly seen in heavily scarified areas.

Where vehicle traffic was relatively light, mechanically protected or resistant individuals were favoured. Species such as *Luzula* spp. and *Alopecurus alpinus* fared the best; however, many demonstrated some resilience to light impact. *Saxifraga oppositifolia*, for example, was eliminated from high traffic areas but mats of this species survived under light to moderate impact with greatly reduced productivity (Babb and Bliss 1974 also reported that *Saxifraga oppositifolia* is resilient to vehicle impact). In most cases, one or two passes by heavy tracked vehicles seemed sufficient to kill 50% or more of the stems. Presumably, mats of *Saxifraga oppositifolia* will regenerate providing all the upright stems and underground parts are not killed.

The meadow tundra at Bent Horn N-72 was the most sensitive type of vegetation to vehicle disturbance. Movement of heavy tracked vehicles at this site had completely ripped the cover of vegetation off some areas and thrown up ridges of organic matter and dead moss. Damage was especially extensive where the active layer was water-saturated. Vehicle damage was also severe at Chads Creek B-64 where heavy traffic close to the sumps had wiped out all the vegetation. These observations agree with those of Babb and Bliss (1974) who noted that mesic sedge and moss meadow habitats are the most likely sites of biological damage because of their concentrated biomass and susceptibility to physical disturbance.

Generally speaking, the effects of vehicle movement on plant communities were much less apparent at the more sparsely vegetated sandy sites such as Cape Fleetwood L-21, Charles Point G-07 and Robert Harbour K-07. Vegetation growing in sandy soils was more firmly rooted and appeared more resistant to this type of disturbance. Widespread uprooting of plants was not evident at the sandy sites.

6.5 Overburden disturbance of soil and vegetation:

Erosion originating in vehicle ruts had developed in the sump infill at Cape Fleetwood L-21, Robert Harbour K-07 and Chads Creek B-64 and resulted in sheetwash of infill downslope by snowmelt runoff.

Deposition of fill overburden was especially noticeable at Cape Fleetwood L-21. This fill was lighter in colour than the soil surface and may have retarded seasonal thaw rates due to increased surface reflection of incoming solar radiation. Such albedo changes probably accounted for reductions in active layer depth 5-45 m downslope of the sump at Cape Fleetwood L-21.

Burial of plant cover by overburden eroded from sumps was observed at Cape Fleetwood L-21, Robert Harbour K-07 and Chads Creek B-64. Some areas at Cape Fleetwood L-21 buried under 10 cm or more of fill were devoid of plants and this type of physical disturbance was the primary cause of plant mortality.

Depth of vegetation by burial occurs due to crushing of plants and depriving them of light and oxygen. These physical effects, however, are temporary. Areas buried by overburden can be recolonized especially by regeneration of aerial stems from underground rhizomes. The initial stages of such recolonization were observed at Cape Fleetwood L-21.

Potential chemical effects of sump fill overburden may be more longterm. Sump fill at the six wellsites was generally high in available levels of drilling fluid contaminants, particularly sodium and chloride. Its dispersion by spring meltwaters thus represented a toxicity hazard to vegetation (especially reestablishing plants) which will persist until toxic levels of ions in the soil are reduced by leaching and other physical or chemical processes.

6.6 Extent and major causes of vegetation disturbance:

While disturbance may result in community simplification (as noted in this study), it also affects the performance of individual species. Measuring species cover, biomass and productivity were not feasible for logistical reasons, hence the record of drilling disturbance effects on the High Arctic plant communities is incomplete. Visual observations suggested that disturbance at the six wellsites significantly affected the performance of all species, especially the mat formers like Saxifraga oppositifolia.

Rough approximations of the extent and overall severity of vegetation disturbance at each wellsite are shown by the CD class maps.

The most disturbed sites were Bent Horn N-72 and Chads Creek B-64. Some contamination from spilled drilling fluids was evident at both sites; however, our results indicate that chemical toxicity was secondary to the destructive effects on vegetation of heavy vehicle movement and construction activity. Problems down the drill hole at Chads Creek B-64 led to extra sump construction (see French

1978a) and passage of heavy vehicles across the site when the active layer was thawed. This additional construction activity virtually wiped out the plant cover over a wide area in the vicinity of sumps. Movement of vehicles across unfrozen meadow tundra at Bent Horn N-72 resulted in similar damage.

Clearly, construction of extra sumps should be avoided wherever possible and heavy vehicle movement across unfrozen tundra should be prohibited. Such restrictions are particuarly important where the vegetation-soil complex is fragile and prone to disturbance. Sites on well-vegetated clay soils (Chads Creek B-64) or in tundra meadow with an extensive organic layer (Bent Horn N-72) should only be drilled when the active layer is frozen.

Vegetation disturbance was also extensive at Cape Fleetwood L-21 and Robert Harbour K-07. Chemical contamination of soil by drilling fluid had occurred at these sites, but destruction of plant cover seemed more related to burial by overburden. At Cape Fleetwood L-21 problems with overburden distribution resulted from use of fine sand fill and placement of the sump at the top of a steep slope. Damage to vegetation could have been reduced by use of a coarser fill and excavating the sump on flatter terrain about 50-80 m from its present location. The same can be said of Robert Harbour K-07. However, damage here was increased by placement of the sump too close to a natural gully. Erosional widening of this gully will cause increased terrain and vegetation disturbance and may result in leakage of drilling fluid wastes.

Damage to vegetation caused by drilling activities was least at Charles Point G-07 and Apollo C-73. Chemical contamination from drilling fluids appeared to be the main cause of disturbance at Charles Point G-07. Damage resulting from vehicle movement was mainly confined to areas immediately adjacent to the drilling sump and vegetation downslope was largely unaffected. Overburden burial of plants had not occurred because crushed stone and gravel were used to backfill the sump rather than easily eroded fine sand. Terrain disturbance at Apollo C-73 was considered during drilling due to sump overflow problems demanding construction of earthen dikes. Much terrain damage was still visible in 1977; however, the effects on vegetation were slight because the original plant cover was extremely sparse. Chemical contamination of soil by drilling fluids and subsequent effects on vegetation were negligable at this site.

6.7 Recovery of disturbed sites:

Revegetation of areas where damage has occurred is desireable from both an aesthetic and ecological standpoint. Destruction of vegetation at wellsites and associated terrain disturbance is unsightly and, at worst, may deplete forage available for herbivores. It can be argued with some justification that these effects of drilling activities in the High Arctic amount to very little on a regional basis. However, at the local level, destruction of plant cover represents a definite disruption of the arctic environment.

Disturbed sites where appreciable vegetation recovery has occurred are rare as most of the drilling activity in the High Arctic has been over the past 6 or 7 years. This represents a short period in an area where plant growth rates are very slow. Despite the short recovery times, though, some revegetation was noted at all six wellsites visited.

Some regeneration of mosses such as *Pogonatum alpinum* var. *septentrionale* and *Ditrichum flexicaule* in disturbed areas had occurred at Bent Horn N-72, but rates could not be determined. The wet meadow tundra at this site seemed the most favourable for regeneration. Such areas, however, are rare in the High Arctic.

The moss *Ditrichum flexicaule* commonly occurred in highly disturbed areas at dry sites such as Charles Point G-07 and Robert Harbour K-07. Absence of a rounded moss blanket morphology at the margins of most denuded areas suggested that encroachment by mosses was slight. Regeneration of *Ditrichum flexicaule*, presumably, was from remnants of original colonies which had not been entirely destroyed. Mosses normally appear rapidly in favourable microsites (Babb and Bliss 1974), and, where vascular plants afford protection from wind and dessication, they multiply concurrently with these larger species. Mosses and higher plants appear to exist in a mutually beneficial relationship. Most higher plant seedlings were found between moss shoots which offer protection in much the same way as fully grown higher plants protect the mosses.

Lichens, except for *Thamnolia subuliformis* and occasional *Cetraria* spp., were completely absent from most heavily disturbed areas. Lichens grow extremely slowly, and no indications of successful re-invasion were noted.

Very little lateral re-invasion by rhizomatous species from adjacent stands had occurred at any of the sites. Erosion of disturbed soils had removed the small amount of organic material present in surface horizons leaving sand (Cape Fleetwood L-21, Robert Harbour K-07), sand and fine gravel (Charles Point G-07), coarse gravel and clay (Apollo C-73), or clay (Chads Creek B-64). None of these soil types seemed particularly favourable to growth of rhizomes. At Bent Horn N-72, even in places where the organic layer was still intact, invasion by rhizomes was negligable, it is probable that an environmental stimulus, either intrinsic or extrinsic, is required for the tillering of rhizomatous High Arctic species (Kershaw 1962). Such a stimulus appeared to be lacking at the six wellsites. Tillering may also have been inhibited chemically due to soil contamination by spilled drilling fluids.

While physical disturbance kills the aerial portions of plants, subsurface rhizomes are commonly unaffected. Regeneration of the aerial parts of species such as *Alopecurus alpinus* and *Luzula* spp., observed in disturbed areas, was mainly from rhizomes present in the soil originally. This method of plant recovery was particularly important at sites where disturbance had resulted from overburden burial, e.g. Cape Fleetwood L-21.

Recolonization of denuded areas at the six wellsites appeared to be accomplished most efficiently by stoloniferous species, e.g. *Alopecurus alpinus* and *Luzula* spp., and prolific seed or bulbil producers, e.g. *Papaver radicatum*, *Saxifraga rivularis*, *Oxyria digyna* and *Stellaria monantha*. The more slow-growing mat formers, such as *Saxifraga oppositifolia*, were not conspicuous where severe disturbance had occurred. Babb and Bliss (1974) have indicated that slow-growing woody and semi-woody perennials such as *Salix arctica*, *Dryas integrifolia* and *Saxifraga oppositifolia* do not become conspicuous until long after the more efficient high seed producers have invaded. Growth of semi-woody High Arctic species can only be measured in terms of millimetres per year. Regrowth to maturity will thus take many years (probably greater than 10).

Our data allow no generalizations to be made about special capacities of 'colonizing species' at High Arctic sites. Because invading plants have very little overall effects on the habitat, autogenic processes favouring seral community development do not appear significant (Babb and Bliss 1974). Recovery noted in disturbed areas was mainly a question of simple simultaneous regeneration by the native species present.

Under certain circumstances a few species can be favoured by disturbance. Such 'hemerophiles' (Kuc 1972) achieve greater vigour and ecological importance in disturbed rather than undisturbed, mature communities. In the sparsely vegetated High Arctic, where competitive interspecific effects are largely absent, hemerophile development may occur as a result of disturbance rendering the habitat temporarily more favourable to plant growth in general. Individual species with special exploitative capacities can gain dominance in such situations. The advantage is eventually lost as the site reverts to its original condition and species with little exploitative capacity, but with a high survival ability, slowly reinvade.

Various types of disturbance can potentially enhance plant growth. Fertilization by disposal of water-diluted drilling fluids may fall into this catagory. Deposition of ashes from burning refuse is a common disturbance of this type (Babb and Bliss 1974). Slight surface scarification can remove saline crusts from dry surfaces to the temporary advantages of some species (Beschel 1963).

Many species act as hemerophiles under appropriate conditions (Babb and Bliss 1974); however, a few of them have exceptional growth qualities in disturbed High Arctic conditions. Hemerophilic species noted at most of the wellsites included Alopecurus alpinus, Luzula spp. and Oxyria digyna. Alopecurus alpinus has been frequently cited as a hemerophile (Beschel 1963, Porsild 1964, Kuc 1972, Babb and Bliss 1974). Rapid root replacement (1-4 years) may be the primary reason for this species' success in recolonizing disturbed areas (Addison and Bell 1976).

Alopecurus alpinus has been cited by Babb and Bliss (1974) as a species with potential for artificially rehabilitating sites where soil stabilization or renewal of an organic layer is desirable. While this species was undoubtably the most successful hemerophile at the six wellsites, its artificial use as a recolonizer would likely be impractical due to slow growth and regeneration rates in the High Arctic. Emphasis in site restoration techniques toward developing favourable microsites for natural recolonization is a more practical proposition. Creating roughened surface conditions on fill materials to provide shelter for recolonizers would greatly assist natural rehabilitation.

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